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Technology Development During Manned Space Flight

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Germany: Technology Development During Manned Space Flight

Evaluation of Technological Consequence of Future Manned Space Flight

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[Article by A. Grunwald, G. Weckwerth and J. Fromm: "Technological Consequence Evaluation of Future Manned Space Flight: The Discussion for Justification and Man's Role"]

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1. OVERVIEW

This article covers manned space flight in a special and novel way. The subject of this concern is the discussion to justify space flight which has been going on for some time but which seems to be leading to a dead end, particularly in view of tight public funds, but also on account of presumably insufficient prospects for manned space flight.

The purpose and goal of space flight are being subjected to critical analysis with the help of a newly-developed set of instruments represented by technology consequence evaluation involving a combination of systems-analysis arguments and ethical principles. Contrary to other areas of technology development, the basic problem in space flight is not to assess desired purposes and undesirable side effects; instead, the problem is to justify space flight to society: what are the purposes that are being pursued by means of manned space flight and to what extent can these purposes justify the enormous expenditures?

The problem of justifying space flight cannot be solved once and for all by analyzing the debate on space flight justification. By arranging objectives, purposes, and resources in an orderly fashion, it does however facilitate a rational discussion that cannot be confined to a tit-for-tat exchange of arguments of differing quality and structure; instead, the participants in this debate must put up with being asked what the presumed standards are and what other unmentioned preconditions might also exist. Systematic analysis in a replicable fashion yields various strategies for justification attempts, ranging from systems-engineering via cultural all the way to political aspects in the broadest sense. These special standards must in each case be presumed to be recognized so that they may serve as justification.

The final result therefore consists of a presentation made to the scientific public and the political establishment so that they may grasp the method employed here and its initial results as aids in the decision-making processes.

2. TECHNOLOGY CONSEQUENCE EVALUATION AND SPACE FLIGHT

2.1. Space Flight and Technology Assessment

Technology assessment has taken hold over the past 10 years as a means for technology control and policy consultation in view of the highly complex developments of technology that are difficult to get a clear picture of. This method emerged essentially from the social sciences with engineering-science disciplines being tied in; it is primarily construed as an attempt to recognize undesirable technological consequences in an anticipatory fashion so that they may be taken into consideration already at the time the decisions are being made and so that they may possibly be brought under control rather early on (1, 2, 3). Technology assessment was and is being applied primarily in energy engineering, transportation, environmental protection, data processing technology, and the waste/reuse/waste disposal complex.

Regarding space flight, on the other hand, technology assessment efforts in Germany are rather in their infancy. Several technology assessment studies, pointing in this direction, have been commissioned in the context of the SAENGER hypersonic technology program. Beyond that, however, there are merely some beginnings in the area of Earth observation.

This finding, however, undoubtedly is matched by an urgent need. In the field of space flight, political leaders demand far-reaching decisions; on the one hand, they want decisions that will be valid for long spans of time, whereas, on the other hand, they want decisions that are connected with heavy expenditures (example: the coming decision on the continuation of European manned space flight). In making such decisions, one must always weigh a wealth of factors, from the desired goals and purposes all the way to technical questions, from political and economic all the way to ecological and social aspects. Technology assessment as a method designed in an interdisciplinary fashion promises precisely this: advising the political establishment on its complex decision-making processes. Why, therefore, should there not be more technology assessment for space flight projects?

The analysis of the reasons why technology assessment took hold only rather hesitantly in the space flight field leads to some rather special features of this technology. Only the following among these features might be mentioned briefly:

-The problem complex consisting of the risk inherent in operating this entire technology as far as larger population segments are concerned; in other fields, this problem complex often rather basically fashions the discussions (for example, in the nuclear energy debate); but when it comes to space flight, it only plays a subordinate or perhaps even negligible role.

-The situation is similar as regards the consequences of space flight for the natural environment. The low launch rate (less than 150 launches, worldwide, on the average over the last 10 years) helped ensure that space flight—in conjunction with environmental pollution—so far has been playing a merely marginal role; in other fields of technology, however, environmental protection problems constitute the main part of the dispute around undesirable consequences deriving from this technology (for example, in the assessment of automobile traffic). Just to what extent considerably expanded future space travel activities would have to lead to a reassessment will depend very much on the technology that is used; this question is currently being investigated intensively.

-Problematic consequences of space flight as far as the work environment of vast population segments are concerned likewise do not play any role or play hardly any role—quite in contrast to what applies to other fields of technology, for example, data processing technologies or display screen work. The social consequences of space flight technology are, to be sure, grasped partially (4) but they are rather of an indirect nature and therefore can be put under the heading of space flight only to a limited extent.

The "classical" motivations behind technology assessment endeavors—in other words, the early recognition of undesirable ecological or social problems or risks to the population resulting from the introduction of new technologies—obviously do not cut any ice in the "space flight" sector. That would appear the reason for the rather hesitant way in which technology assessment experts tackle this sector. In addition, there is the fact that the inventory of technology assessment methods naturally is tailored to its "classical" problem areas and that it is therefore not at all clear whether the subject field of "space flight" can be sufficiently covered with existing technology assessment methods. Further analysis of the special features of space flight is necessary to decide this issue. It leads to the following points:

-Space flight, especially manned space flight, which will be discussed below, very extensively is not subjected to the laws of a commercial market, quite in contrast to many other fields of technology. It must rely on subsidies from public funds and is therefore heavily dependent on specific, detailed policy-making decisions. Instead of a continual train of developments, one can therefore often observe rather abrupt reorientation steps designed to accommodate new political or social orientations and marginal conditions.

-A quantitative record and a statistical processing of parameters used in manned space flight do not make sense due to the fact that these activities depend on decisions and, besides, the scope of these activities is numerically rather small.

-Manned space flight is extraordinarily expensive, as everyone knows. The most serious negative technological consequence of space flight (if one may call it that) therefore appears to be a hypothetical diversion of subsidy funds from other fields, especially from the research budget (see, for example, 5); the opponents of manned space flight maintain that these other sectors are socially more urgent.

-In view of its high costs, manned space flight thus above all brings up the question as to its justification, its socially relevant objectives and purposes (whereas there is no confusion, for example, as to the purpose of a nuclear power plant or ICE's). The purpose and long-term meaning of manned space flight are not clearly discernible from the very beginning; instead, they require clarification.

In the space flight sector, therefore, we are not so much interested in the question as to weighing the positive and negative consequences of this particular technology; instead, we must look at the question as to the purposes of manned space flight: is the statement of these purposes sufficient to justify the heavy expenditures? Space flight, especially manned space flight, must face society's demand for justification. Technology assessment that provides policy-making advice cannot consist solely of the early recognition of hazards; instead, it must above all critically reconstruct or accompany the decision-making process.

Technology assessment oriented in social-science terms does not offer adequate handles for treating such questions. This is why an interdisciplinary team, consisting of staff members of DLR (Space Flight Systems Analysis Main Division, Professor Sax) and philosophers from the universities of Essen (Professor Gethmann) and Marburg (Professor Janich) in the context of the SAPHIR Project, which is promoted by the Federal Ministry of Research and Technology, accepted the assignment of developing a method that will do justice to the described special features of the space flight sector using the example of "Assessment of the Technological Consequences of Manned Space Flight." Systems-analysis, science-theory, and ethical aspects converge there. This article contains an excerpt from the results of this project.

2.2. Technological Consequence Evaluation—Method's Basic Features

The basic idea behind the newly-developed method called "Technological Consequence Evaluation" consists of tying engineering science, especially systems-analysis data and philosophical foundations, together, in the latter case, especially from normative ethics and the theory of science.

Contrary to a widely-held attitude, it is not true that scientific objectivity is impossible when it comes to the question of spelling out purposes and standards. There is no rationality gradient between prescriptive and descriptive (for example, natural science) information. Both of these equally cite self-assertion claims that can be redeemed by means of rational argumentation (6).

It is not the mission of ethics to set up standards; instead, the mission of ethics is to develop basic principles of coping with conflicts that will be invariable in terms of particular situations so that a common ground of understanding can be reached in a discourse on the acceptance of standards that might have consequences in terms of implementing or discarding technical projects. Its basic model is the model of advisement as a special discourse in whose context the basis is to be created for resolving the conflict (7) by means of a rational analysis (a critical exposure of presumed norms) of the arguments used by the parties to the discourse (in this specific case: opponents and advocates of manned space flight).

Ethics makes its contribution to the resolution of this conflict through the following steps spelled out concisely here (see 7, 8, for more detailed explanations):

1.Definition of a terminology that will be crystal clear (and that will be adequate for the particular purposes). This is required because only such a terminology—which is jointly recognized by the parties to the conflict—will facilitate understanding and communication. Many conflicts can be resolved already through reflection of the basic underlying language systems.

2.Rational reconstruction of the purposes and objectives pursued by the parties involved (regarding the introduction of the particular new technology) by means of a discoursing analysis using the selected terminology. The argumentation structures occurring there are arranged systematically by forming purpose-means and purpose-norm structures. This, above all, also includes the critical exposure of unnamed norms that are tacitly presumed to be recognized.

3.Identification of (logical or pragmatic) incompatibilities among purposes leading to a confrontation by the parties involved. On the basis of the reconstruction mentioned in Point 2, above, it is now possible to line up opposing arguments used by the contracting parties within larger structures and thus to determine their valence as regards the underlying norms.

4.Proposals regarding the removal of incompatibilities by specifying jointly acceptable higher purposes or by changing or adjusting the purposes pursued by the contracting parties should be drafted. If this is done successfully, then the conflict has been eliminated. If not, it must be continued.

This is naturally an ideal way of doing things and one will encounter it in real-life discourses only in special instances (by way of an example illustrating the exact opposite, one might think here of the current dispute revolving around European manned space flight). But this does not mitigate against the proposed method; instead, it speaks for it: it facilitates critical distancing from the discussions that are actually taking place and it thus promotes the assessment of decision that have materialized in fact.

In this sense, ethics is normative because it formulates certain specific normative principles through cooperation in practical deliberations (that is to say, debates as to the definition of purposes): if standard x is recognized, then purpose y should be realized. But social agreement must be achieved in the course of the deliberations regarding recognition of the standard x.

The other leg of technology consequence evaluation—that is, systems analysis—on the other hand, puts up descriptive principles about technical systems (systems that are already in existence but that, above all, are first of all planned or still in the thinking stage): its task is to evaluate certain technologies regarding their suitabilities as means for the implementation of purposes that are laid down (or that are set up hypothetically in the course of a practical conference). Its exact place in the decision-making process is the technical conference that provides communication on means toward the attainment of purposes. Systems analysis is therefore employed above all for the purpose of setting up prognoses in the context of technology consequence evaluation as a method that provides assistance in decision-making processes concerning future technologies; these prognoses are established, among other things, on the following:

-purpose-means relationships, social need, practicality, utilization possibilities, potential for further or follow-on developments;

-technical feasibility, practical implementation time frame, cost-benefit ratios;

-means-consequences relationships: what (ecological, economic, political, etc.) consequences can one expect if certain means are chosen?

These prognoses are not forecasts along the lines of social-science extrapolations of observed trends that account for about 90% of all prognoses (9). Instead, target-oriented prognoses are set up and they start with the hypothetical establishment of a purpose, following this pattern: "If purpose x is to be attained, then, from the systems-analysis viewpoint, means y, z, etc., are suitable and they can be used to attain the purpose with the help of expenditure a during time span t via route w." The link between prognosis and the purposes established by society is preserved and one avoids creating the impression that one could predict technological developments "as such." This form of prognosis (also referred to as "normative" prognosis in another context (10)) is closely tied to the scenario technique.

Normative prognosis is tailored to the special features of the space flight sector as stated in 2.1. This is because, on the one hand, it avoids simple trend extrapolations that are impermissible in space flight because there are no laws of procedure or progression and due to the absence of a sufficient number of identical events to serve as foundation for statistical treatment. On the other hand, target-oriented prognosis reflects precisely on the aspect of heavy decision-making dependence: a purpose is set up—as a state desired in the future: the time up to the

achievement of this state is so structured by conditional normative and target-oriented prognoses that the purpose can actually be attained within a succession of states (milestones in projects) and actions.

How should one now construe cooperation between ethics and system analysis in the decision-making process such as it relates to a new technology? In the final analysis, the decision is made on programs, projects, missions, etc., in other words, on technical means. The decision's justification, on the other hand, relates to the specification of purposes inherent in the technology as well as standards from which one can again justify the establishment of the purpose. Ethics is concerned with the relationship between norms and purposes; in contrast, the purpose-means relationships represent the task area of system analysis. The result is the following logical structure of a hypothetical syllogism by way of a rather hefty simplification. In this syllogism, ethics supplies conditional normative super-principles and system analysis provides descriptive sub-principles:

Super-principle: If norm x is recognized, purpose y should be attained (task of the ethics of technology).

Sub-principle: Technical resources q, r, s (with properties e (effort, implementation time frame, consequences, etc.)) are available (task of system analysis) to attain purpose y.

Conclusion: Technical resources q, r, s are to be developed and used to attain purpose y.

This rather simple figure obviously hides some problems. The problem of weighing must be mentioned here first of all: according to which criteria should one compare several means or purposes that may be considered? Here again, one must point to standards that must supply criteria for the required comparisons.

On the other hand, there is the question as to how one should handle unintended or negative technology consequences. Forecasts of such undesirable consequences are included in the deliberation via a feedback process. That is an attempt to minimize the purposes and means by altering them. In the final analysis, it is again the socially recognized norms that will decide the measure of acceptable negative consequences.

The form which was illustrated here very briefly shows the shaping of technology as a result of rational argumentation about standards, purposes, and means. This viewpoint provides critical distancing from the factual aspect where technology development is often determined by other factors (lobbyism, power relationships, tactics, etc.). In this sense, the assessment of technology consequences emphasizes argumentative discourse with whose help society constructs its technology.

3. RECONSTRUCTION OF THE DISCOURSE ON JUSTIFICATION

A discourse is generally considered to be a sequence of (verbal or written) language actions that are presented by various parties on a particular topic. The parties to the discussion that comment on the topic of "Justifying Manned Space Flight" are above all government agencies, party politicians, scientists, media, associations, research installations, and industry.

The past and current discussion on manned space flight takes place in manifold forms: speeches, announcement by political parties or associations, interviews, position statements from ministries, target programs by space flight installations, definitions of purposes and objectives on specific space flight missions or programs, commentaries in many different forms from science, the media, or industry.

The reconstruction of the discourse is not a retelling or simple collection of arguments found there; instead, these arguments are analyzed with a critical intent. Attention is focused particularly on the exposure of presuppositions, that is to say, standards that are tacitly assumed to be recognized. The discourse reconstruction gains epistemological value (11, 12) by virtue of this systematic and critical analysis of arguments that are articulated during the factual discourse in a disordered and intuitive fashion.

The space flight discussion is in each case marked by the cultural background of the different countries that pursue space flight. In the following, we will therefore first of all examine the discourse in Germany. In a second step, we will look into the purposes of space flight that are cited mostly in other countries.

3.1. Basic Features of Discussion in Germany

The discourse on manned space flight runs mainly along three lines of argument in Germany: economic, natural-science-technical, and political. Both advocates and opponents of manned space flight employ arguments from these fields. Only a few of the essential arguments can be mentioned here for reasons of space.

a) Economic Argumentation Patterns

The debate in Germany is extensively determined by the measurement of manned space flight using the yardstick of economic benefit, often boiled down to the profit or loss that can be stated in monetary terms (13). Such widely differing purpose complexes as political, scientific, and economic ones are judged with the help of a single instrument, that is, the cost-benefit analysis. Here it is presupposed that only that which promises profit can be considered as being "meaningful" in the societal context. This side to the debate does not brook any other attempts at justification.

This argumentation sample was used above all when Europe got into manned space flight with the "Spacelab" Program; it was repeated later in connection with the Columbus debate. At that time, the advocates of manned space flight advanced far-reaching hopes as to the industrial marketing of results deriving from µg research; but these hopes proved to be premature, to say the very least.

In the final analysis, the strengthening of this line of argument—which was accomplished by many proponents—backfired on manned space flight: from the economic viewpoint, manned space flight is a losing business and will continue to be so for the unforeseeable future. It should therefore be stopped, looking at it from that angle alone.

This approach can be criticized as constituting an extremely narrow definition of rationality. The quality of human life can under no circumstances be measured only with the help of the concept of economic benefit (no matter how useful this may be for certain purposes). This is because boiling everything down to the "money" yardstick disregards important real-life action and purpose interrelationships and therefore requires supplementation by means of other "trans-utilitarian" lines of argument.

b) Argumentation Samples Based on Natural Science and Technology

Research projects, above all in the fields of extraterrestrial activities, Earth observation, materials research, and biomedicine under conditions of weightlessness are essential elements in justifying the German commitment to space (14). On the other hand, there is dissent on the meaning of the manned aspect of space flight (15, 16). The proponents stress the irreplaceability of cooperation provided by "scientific astronauts" and the significance of experiments under outer-space conditions as far as basic research is concerned (16). The opponents have the following objections to that line of argument (5, 15):

-man in space is also a disturbing factor (such as for µg experiments);

-his tasks can essentially also be performed by automats or robots;

-a large part of research in space, for example, in medicine, merely is intended to facilitate the presence of man there (this being a charge of circular reasoning);

-the costs of manned space flight could threaten basic research in other sectors.

The attempt to justify manned space flight above all with arguments rooted in basic research thus led to even more uncertainty and to the question as to the justification of this basic research in outer space. Instead of solving the problem of justifying manned space flight, the entire problem complex was merely shifted to the question of justifying expensive basic research.

c) Political and Cultural Argumentation Patterns

Political arguments, such as the significance of manned space flight to European integration or international cooperation, the confirmation of each country's own reliability regarding European agreements or the like are of course mentioned by political establishments as such and do play an important role there in the decision-making processes (17, 18, 19). But the opponents do not address this aspect sufficiently by either ignoring these arguments or by immediately suspecting them as nothing but ideology.

The analysis of the discourse shows that political grounds were essential driving factors behind manned space flight in other countries—the most outstanding example here is the "race to the Moon" during the East-West conflict—and they still are just that (for example, present-day considerations on cooperation with the CIS). Such justifications are certainly problematical: in the context of the historical situation itself (Cold War), they undoubtedly looked rational; but today's altered situation does conceal the rationality that prevailed at that time. Political (and to a lesser extent, also cultural) reasons thus differ in terms of their justifying character from economic or scientific grounds: they are more strongly tied to the particular current social constellations and they are therefore potentially short-lived. But this must not lead to underestimation (see also 3.2).

The discourse analysis furthermore reveals that there is one important distinction that is often not noted. Criticism of individual space flight projects and overall criticism of manned space flight as such are not differentiated. But this is where care is required: from (undisputed) shortcomings of specific projects, one must not conclude that manned space flight is generally senseless, such as this is being done in part (13).

In the following, we will select the overall, general approach by analyzing specific purposes of manned space flight.

3.2. Trans-Utilitarian Purposes of Manned Space Flight

By trans-utilitarian, we mean here "not recordable with the help of the economic, that is to say, monetary definition of benefit." Such purposes indisputably played an important role in past manned space flight (both in the public discourse and in practical decision-making). Apollo is the best-known example of a space program that was carried out far away from any cost-benefit analyses and that nevertheless was met with extensive approval. This historical argument however is not enough to prove the relevance of trans-utilitarian purposes because this way of arriving at a conclusion would of necessity have to end up as a naturalistic misconclusion. Instead, the idea is to show that the attainment of certain trans-utilitarian purposes can contribute to resolving societal shortage situations. This is done by means of presuppositional analysis: one tries to determine which norms would have to be accepted in order to permit the normative conclusion that these trans-utilitarian purposes (using the resources of manned space flight) should be attained. Factual acceptance of the norms must be decided in the course of the social-political discourse. Here we tie in with politics and the

factor of policy counseling that is inherent in the evaluation of consequences deriving from technology: justified hypothetical statements become possible via purpose-norm relationships.

In the following we will describe some of the trans-utilitarian purposes that were analyzed. At this point, one can only give a brief description; we will cover only the purposes of "international cooperation" and "overview effect" in a somewhat more detailed fashion and by citing examples.

a) Leadership

In the discussion in the United States, the purpose of "leadership" (winning a leading position) assumes an outstanding position. The leadership role—pointing up visions and advancing in their practical implementation—is not sought in all fields but only in "key areas," such as national security, science, and technology, etc. This claim is justified with a reference to an allegedly special responsibility in the world. The meaning of freedom also plays a role along with the political dimension: "leadership" then signifies the freedom of a nation to pursue its own actions and to be independent of the actions of others.

b) Pioneering

"Pioneering" addresses the border-crossing moment of manned space flight, the aspect of the permanent transcendency of the situation. Boundaries (of knowledge, of technical know-how, of areas in which human beings can live and work, etc.) are considered by man as a challenge to cross these boundaries, that is, from the anthropological angle. Obviously, manned space flight (but also unmanned space flight) can make unique contributions to this purpose by entering new regions and by facilitating hitherto inaccessible research.

c) National Identity

Today, technical and scientific star performances are means for boosting a nation's identity. If such a purpose can be considered as being justified, then the concept of "nation" must have a positive content so that it will facilitate a "good life" for the individual (20). That brings us to the question as to what national identity can be grounded on in terms of common origin or common future. Manned space flight can also help (as can other future undertakings) in guaranteeing national identity not only by falling back on common origins but also by making reference to a future that must be fashioned together.

In the European context, space flight here—through cooperation within ESA—moreover creates the possibility of building up a supranational identity with a view to future tasks that must be accomplished together.

d) European Autonomy

To improve Europe's importance among space-flight-pursuing countries, the ESA member states established the purpose of attaining European autonomy regarding the implementation of manned space flight—as a powerfully symbolic and important sector of modern technology—which also injected heavy (foreign-policy and security-policy) political accents into the equation (18). The goal was to overcome the prepotent position of the then superpowers and to replace it with an equal partnership arrangement, to strengthen European identity and to advance integration.

e) International Cooperation

The limited perspective of a nation or a continent should be discarded in order to grasp manned space flight as a task for all humanity. One pragmatical reason here is the bunching of material and intellectual resources in order to achieve, together, that which individual states are not capable of pulling off. Moreover, a joint undertaking can develop force for integration and promote worldwide understanding (17). Presuppositional analysis then allows us to formulate the following conditional normative statements:

If the norm is presupposed:

-more efficient performances should be achieved in science, technology, and the economy;

-homogeneity and the compactness of mankind should be anchored more deeply in human consciousness by reducing hostilities between nations and by supporting developing countries:

-global peace should be secured through cooperation;

-and international cooperation for the "manned space flight" project yields more efficient performances and contributes to peaceful coexistence among nations;

then one can consider: the trans-utilitarian purpose of "international cooperation" as being justified and as having to be implemented with the help of large-scale international projects under the heading of "manned space flight."

f) The Overview Effect

Because of manned space flight, man was able for the first time to view the Earth in its totality ("Overview," 21). Eyewitness statements by astronauts made their emotional and aesthetic experience accessible to society. The evaluation differs depending on whether these observations are interpreted from the anthropocentric, geocentric, or cosmocentric angle. On the one hand, there is emphasis on man's universality, on the ability to leave Earth in an artificial environment (with a time limit on it); on the other hand, the Overview is also interpreted as an obligation, as a responsibility that is to be assumed for Earth, the "home planet." Manned space flight thus cannot bring about a decision between the various world views. But it does supply new arguments for the discussion. Therefore we can say this:

If the following is presupposed as norm:

-a global view is to be obtained over the entire Earth;

-aesthetic and emotional experiences about the Earth as a whole should be attained and communicated;

-ideologies (anthropocentrism, geocentrism, and cosmocentrism) should be examined to form a clear and consistent view of the world;

-and manned space flight makes it possible to gain a global picture of the Earth and to obtain aesthetic experiences of it;

then one can consider the purpose of "overview effect" as being justified and as having to be attained with the help of manned space flight.

The justification of manned space flight by means of trans-utilitarian purposes, however, runs into two special problems.

First of all, most of these purposes are not specific to space flight, that is to say, they can be attained also by means of other societal undertakings. One must in each individual case investigate to what extent and under what conditions manned space flight is particularly suited for contributing to the resolution of specific societal shortage situations as a means for the attainment of trans-utilitarian purposes. But going into this question requires yet other analyses.

On the other hand, some of the trans-utilitarian purposes entail the danger of being rather short-lived because they reflect societal shortage situations that can change quickly, as we know (as pointed up by the end of the East-West conflict). That does not by any means reduce its significance, but it does lead to problems if these plans are to be used in practice. Here is why: during the usually long-drawn-out practical implementation of manned space flight projects, there may, so to speak, be a change in the fundamental situation on whose basis the fundamental decision was made in the first place.

Other trans-utilitarian purposes are of an anthropological nature (pioneering, overview) and are therefore long-term stable purposes precisely because of that. On the other hand, they, too, create problems because they must always be viewed in balance with other more short-term purposes.

These problems alert us to problems of basic principle in the decision-making process regarding complex technologies. They reflect really existing difficulties instead of dissimulating simplicity. These problems therefore must not entice us into disregarding trans-utilitarian purposes or underestimating their significance. The exact opposite is the case and it is precisely that which the above-mentioned problems alert us to.

4. MAN'S ROLE IN OUTER SPACE

Let us begin with a triviality: the special aspect of manned space flight is represented precisely by the fact that it facilitates man's stay in space. This fact, to be sure, is rather banal, but it is quite important because this is the point of departure for any justification of manned space flight as against unmanned space flight. In other words, we must look for the peculiar aspects that result from the presence of human beings on board of spacecraft.

In unison with the methodology, explained in Section 2, the point of departure selected for the determination of the essential aspects is the reconstruction of the discourse by means of which the purposes of manned space flight are to be reconstructed (a small segment of that was discussed in Section 3). These purposes are arranged systematically and purpose-objective and purpose-means structures are drawn up. The result of the classification of various possible justification structures (indication of purposes and objectives for resources) will be an evaluation of the various roles played by man in space.

4.1. Aspects of Manned Space Flight

The purposes of space flight (which, in other words, can answer the question as to "what for") can be classified in various ways. A first classification level concerns the relationship between purposes and space flight:

-specifically space-flight-related purposes: purposes whose attainment takes place exclusively or very advantageously through space flight (for example, μg research, exploration of alien planets, in situ, etc.);

-purposes not specifically relating to space flight: purposes that can be attained also by means of other undertakings (large-scale technologies, such as, for example, energy procurement by means of nuclear fusion but possibly also by undertakings of another kind, such as environmental protection agreements or technology projects). Purposes in this area are, for example, international cooperation, spinoffs, etc.

A second classification level is oriented by the relationship between the purposes and the concept of economic benefit. The following are distinguished:

-utilitarian purposes (connected with the attainment of an economic benefit) -and trans-utilitarian purposes.

Regarding these two classification levels—which are independent of each other and permit systematic classification—the structure of the purposes of space flight can be pictured as a matchup of purposes in a 2x2 matrix. Here are examples of this arrangement:

Earth observation:	Utilitarian, space-flight specific
Medical research, in μg:	Trans-utilitarian, space-flight specific
Settlement of outer space:	trans-utilitarian, space-flight specific
Spinoffs:	Utilitarian, non-space-flight specific
International cooperation:	Trans-utilitarian, non-space-flight specific

Now, on the other side in the current space flight discussion (17, 19), there is another setup involving differentiation according to the following purpose

groups: "fostering benefit on Earth," "science and research in space," and "exploration of space for man." Roughly speaking, this grouping can be matched up as follows with the above systematic arrangement:

Fig. 1. Classification of Space Flight Purposes

Key: 1—Space flight purposes; 2—Space-flight-specific purposes; 3—Non-space-flight-specific purposes; 4—Utilitarian purposes (fostering benefits on Earth); 5—Trans-utilitarian purposes; 6—Science and research in space; 7—Exploring space for man.

The purposes of space flight pursue objectives (these are the attributes of the purposes for whose sake the purposes seem desirable). We will list only a few of them here so as to make the structures clear:

-political objectives (European integration, securing peace, protecting the population, environmental protection, etc.);

-economic objectives (raising the living standard, economic growth, attaining profits, etc.);

-scientific-technical objectives (expanding knowledge, systematizing knowledge, finding new practical applications, etc.);

-cultural objectives (fashioning the world image, change in consciousness and awareness, transcendency of situation, identity as a world society, etc.). Purposes can be justified by stating objectives (the latter can be restated in the form of norms). This is served by the purpose-objective structure that assembles the manifold relationships of purposes and objectives. But it would take us too far afield to go into that.

On the other hand, the purposes of space flight are tied to the means for implementing them likewise by means of structures. Here we will only present a classification of resources which we will come back to later. We distinguished two types of resources:

a) Organizational resources:

This is the level of program design and project implementation in political, organizational, and operational respects. Here are the options for manned space flight: each nation going it alone, joint flights in the programs of Third World countries, European cooperation ESA, or international equal cooperation.

b) Technical resources:

On this level, we find those resources that traditionally are considered space flight resources (transportation systems, orbital systems, operating installations, etc.). These technical resources for the attainment of space flight purposes are further differentiated in terms of manned and unmanned resources.

Fig. 2. Arrangement of Space Flight Resources

Key: 1—Space flight resources; 2—Technical; 3—Organizational; 4—Manned; 5—Unmanned.

On the basis of this analysis of the purposes of manned space flight and its relationship to objectives and resources, one can now try to figure out what aspects of manned flight could at all be essential when it comes to justifying these undertakings. Various classes of justification for manned space flight can be identified, particularly on the basis of purpose-means structures:

-the system-engineering justification comes through the correlation of technical resources and specifically space-flight-related purposes. Example: as science astronaut, man participates in the attainment of scientific purposes in space, and he does this by operating technical resources, performing experiments, etc.;

-the justification that goes beyond system engineering aspects relates mostly to the correlation of organizational resources and trans-utilitarian purposes. Example: "International cooperation" as trans-utilitarian purpose requires corresponding forms of organization (project structures) in order to be implemented;

-the large-scale technical justification comes above all through the correlation of organizational and technical resources with non-space-flight-specific purposes. Example: the "technology transfer" purpose is non-space-flight-specific, but it can also be attained by corresponding technical resources available through space flight.

These classes point to different roles played by man and thus lead to a setup of his various past roles in space, as follows:

Fig. 3. Aspects of Manned Space Flight

Key: 1—Aspects of manned space flight; 2—Presence of astronauts in space (activities, experiences, functions); 3—Manned space flight as large-scale technology; 4—Man's system-engineering role; 5—Aspects going beyond system-engineering role; 6—Astronaut as reporter and eyewitness; 7—Astronaut as surrogate and identification symbol.

This arrangement can also be set up analytically. The first distinction is derived from whether one focuses on the individual human being in space and his contributions, functions, and experiences, or whether the emphasis is on manned space flight as a large-scale technology, as one of the most demanding undertakings tackled by man; in the final analysis, the individual astronaut is of no interest (the point entitled "Manned

Space Flight as Large-Scale Technology" is discussed only fleetingly because, in the following, we will only look at man's role).

Any further differentiations among the manifold aspects involved in man's presence in space are made on the basis of different purposes that are pursued with the help of this presence. They will be discussed in greater detail below.

4.2. Man's System-Engineering Role

Man is considered a subsystem within a bigger system, that is, the functionally interrelated "man-machine system" that makes it possible to execute a space flight mission. That includes the space vehicle itself (mission and utilization parts) and the required ground infrastructure (launch facility, control center, training center, etc.). Man's system-engineering role in space is now defined by the following:

a) extent and type of requirements determined by his presence, as well as

b) type and scope of his activities to the extent that they are connected with the operation of the overall system.

Man is thus construed as a part of the system within which he must perform certain tasks. He makes contributions to the success of the "mission" system as a partner of the technical equipment and is thus a means for the attainment of purposes.

That obviously covers only a portion of human activities, that is to say, man's functional role in the system context, which he can play by virtue of his specialist skills and technical expert knowledge as pilot, scientist, engineer, etc. The question as to the meaning of manning thus is posed as follows on this level of argumentation: what does man contribute to the system's functioning? This system-engineering question is, as a rule, tied in with the utilitarian aspect: what does it cost to put a man in space and what is the relationship between the benefit produced by man and these costs? In this sense, man must face the competition he gets from other means for attaining the same purpose: that is, the competition from unmanned space flight, the competition from automats and robots.

A justification of manned space flight with the help of system-engineering arguments thus also starts with the analysis of man's system-engineering role and from that draws conclusions such as this one: "If the (space-flight-specific) purpose x is t be attained, then for system-engineering reasons, man's contribution y is necessary or advantageous, that is to say, it is more cost-effective than implementation by automats."

That means that the justification of manned space flight in terms of system engineering takes place essentially through the correlation between technical resources and space-flight-specific purposes.

The system-engineering question is precisely an essential level of the current public discussion on manned space flight (5, 15, 16): man, construed purely as a means to an end, to ensure system functions from the aspect of the relationship between benefit and expenditure. The reverse side of restricting the discussion to the instrumental aspect of man in space consists in the fact that the replacement of human activities by automats concerns precisely these functional activities that are carried out by man; and this replacement of human activities with automats keeps increasing as automation possibilities make progress. Replacing man's operations with automats, looking at it from this angle, is most extensively—a function of the particular development state of robotics—merely a question of failure risk as well as the technical and monetary expenditures. From the system-engineering aspect, the justification of manned space flight thus can always be made up only in specific terms, with a view to a particular task assignment, and gradually, in the context of the particular available technical resources or those that are within reach.

System-engineering arguments therefore influence the justification structure (the indication of purposes and objectives relating to a specific project) only by virtue of restrictions or recommendations as to the choice of resources.

A system-analysis evaluation of the manning aspect starts with the possible and required system-engineering functions performed by man in outer space. Here they are:

-Man as the executor of technical in-flight maneuvers, as pilot or commander, in relation to the operational handling of the space vehicle.

-Man as science astronaut to perform experiments, to monitor processes and progressions, and to interpret data.

-Man as an experimental subject in biology, human medicine, or psychology.

-Man as engineer for attendance and maintenance, spare parts assembly, repair or recovery of elements of the orbital infrastructure.

-Man as problem solver in unforeseen cases, emergencies, or disasters (emergency/troubleshooting).

By way of supplementing this kind of qualitative assessment of possible contributions from manned space flight, one might also try to quantify the significance of man's system-engineering role—in what is of course a very rough way—perhaps in the following steps:

0: no human contribution required;

1: man's contribution consists in supporting and optimizing instruments and could therefore be replaced by additional automation without any major effort;

2: man makes an essential contribution to such an extent that the attainment of the particular purpose is cheaper manned than unmanned;

3: absolute requirement: the particular end cannot be attained without man's contribution in space.

The advantage of this type of evaluation consists in the fact that one can thus facilitate a quick overview of the degree of significance of manned space flight for the particular purposes.

With this kind of pattern, it is possible to judge the significance of manning, both for space-flight-specific super-purposes (examples here are Earth observation, research under microgravitation, buildup of orbital infrastructures, in-situ extraterrestrial exploration) and for specific missions. These judgments can be made only in relative terms, both as regards the established purposes and as regards the state of the art; these evaluations must be based on system-analysis knowledge concerning the mission requirements and the possibilities of automation. The reference to purposes to be attained through space flight is always preserved here.

4.3. Aspects Going Beyond System-Engineering Role

This point is devoted to those aspects of human activities and experiences that cannot be subsumed under man's system-engineering role. We are talking here essentially about two aspects of astronauts' presence in space (which spring from the analysis of the reconstructed trans-utilitarian purposes, see Part 3): the astronaut as reporter or eyewitness and as identification symbol.

A justification of manned space flight by means of such aspects of human presence in space relates primarily to the correlation between organizational resources and trans-utilitarian purposes.

4.3.1. The Astronaut as Eyewitness and Reporter

Our interest is focused here not on the system-relevant functional requirements but rather on man's role in all of the manifold experiences accessible to him. This concerns above all aesthetic and emotional experiences. But the human ability of associative pattern recognition also plays a role here: "seeing" does not mean the mere registration of images (as if by a camera); instead, it implies simultaneously orderly arrangement and reflection, in other words, recognition. Naturally, this subjective level of personal experiences must be crossed if one is to arrive at a socially demanded justification of manned space flight. Astronauts play a decisive role for society as reporters and (eye)witnesses of experiences and events that cannot be grasped in any way other than by means of manned space flight. The astronauts assume this (multiplier) role in the course of lectures, discussions, publications, etc. The justification of manned space flight by arguments from this angle therefore must stress the astronaut's witness role and must clarify the significance of that role as far as society is concerned.

In this context, we must mention above all the "overview effect" as a trans-utilitarian purpose. A picture of the Earth as a whole can clarify the compactness and sensitivity of the earthly biosphere and can emphasize its beauty against the black and life-threatening background of the cosmos. Such experiences demand eyewitness reports if they are to take effect in social terms, that is to say, if they are to strengthen the sense of responsibility for the Earth.

4.3.2. The Astronaut as Identification Symbol

Another aspect of the presence of astronauts in space beyond the system-engineering role is their significance as representatives, be it for a nation or for mankind as a whole. Their spearheading role and their outstanding position facilitate identification with the astronaut. This effect is particularly important in the group of trans-utilitarian purposes, although in different ways:

-"National identity" (here one might think of the hoisting of the American flag on the moon while the cameras kept grinding away);

-"International cooperation" (that could become significant in case of an internationally composed mission to Mars whose participants then would no longer be viewed as the emissaries of nations but rather as the representatives "of mankind");

-"Pioneering" (astronauts here are the border-crossing spearheads, as were the explorers in earlier times).

Astronauts, however, also serve as identification symbols for the world-image-fashioning force of the reflection from the man-technology relationship and the man-nature relationship that are required by virtue of the new life maintenance systems. This is because the astronauts, during their stay in space, live in an environment that was made by man himself and that was created artificially for specific purposes and in an efficient manner; during this (limited) time, they are independent of the Earth's biosphere—yet another success of technology in terms of protecting man's life also under the conditions prevailing in space that are absolutely hostile to human life.

All of these mentioned aspects obviously require manned space flight. But to justify manned space flight with arguments of this kind, one must furthermore clarify to what extent the possibility of identifying with astronauts can have socially (nationally or internationally) relevant consequences, in other words, to what extent these trans-utilitarian purposes serve to resolve societal shortage situations. That can be judged in each case only in specific historical, political, and cultural constellations; and that is a task for politics.

4.4. Justification by Means of "High-Tech" Arguments

Another strategy to justify manned space flight consists in stressing the "high-tech" aspect. Purposes that are mentioned in this context are the spinoff potential,

technology transfer, technology for the future, in the final analysis, also the strengthening of the national economy and the creation of high-grade jobs (17, 19). This justification—which is certainly disputed—comes about primarily due to the correlation between technical and organizational resources, on the one hand, and non-space-flight-specific purposes, on the other hand.

Here, man obviously only plays the role of providing an occasion for special technical developments (spacecraft recovery technique, life preservation systems, rescue systems) with a special demand for reliability—in the hope that this technology will have positive effects in other sectors. Man's ultimate presence in space does not play a role here so that this aspect will not be further pursued at this point.

5. PROSPECTS OF EUROPEAN MANNED SPACE FLIGHT

The method of evaluating the consequences of technology is aimed at critically keeping up with the decision-making processes regarding technical developments, in this specific case, manned space flight. Now, political decisions on new techniques as a rule relate to specific space flight projects (for example, the impending decision on the continuation of the ESA long-term plan). If the evaluation of technology consequences wishes to accompany such decision-making processes, then it must permit statements precisely on this level.

By way of examples, we therefore want to apply the evaluation of the consequences deriving from technology to some conceivable specific projects involved in future European manned space flight so as to test the possibility of contributions to present-day decisions on the progress of Europe's manned space flight. In particular, we want to make a critical evaluation here of the frequently cited argument that one must "keep options open" in manned space flight. At this point, we can only discuss the basic features because this part of the SAPHIR Project is currently still in the processing stage.

The following conceivable projects for the future will now be analyzed with a view to European manned space flight:

- exploration of Mars,

- resources from outer space,

- procurement of energy by means of solar-powered satellites,

- production in outer space under µg conditions.

This selection was made from several aspects which, together, are covered by the goal of attaining the greatest possible variety in the evaluation. Man's role or the role of manned space flight will thus emerge in widely differing ways in each case. The justification problem complex, the underlying purposes and objectives, but also the risks and practical implementation conditions differ greatly in the projects chosen.

To clarify the environment in which European manned space flight has taken place and still takes place today, we first of all want to make an inventory. Here we will discuss various aspects from the focal point of European capacities and past and future conceivable cooperation models.

The specific project analysis is subdivided into two parts. In the first part, we are concerned with recording the future prospects in the context of evaluating the consequences of technology (ethical and system-analysis statements on the project); in the second part, we will concentrate on the question as to the extent to which the establishment of purposes aimed at the implementation of the contemplated projects for the future will have consequences as regards present-day manned space flight. In other words: what possibilities for action can we consider today or what possibilities are required so that such projects can at all be implemented in the future?

In the first part, we use the developed set of instruments provided by technology consequence evaluation. The contribution made by ethics consists of an analysis of the purpose-means and purpose-norm structures underlying the projects. From the system-analysis viewpoint, we set up descriptive prognoses on practical implementation conditions, cost-benefit ratios, practical implementation time frames, technical requirements, practical implementation risks, and the consequences of practical implementation as such. From the methodological viewpoint, it is particularly interesting here to note that individual projects are analyzed descriptively and are also judged in normative terms.

On the basis of the evaluation of technology consequences, such as it was made, it will then be possible to ask and answer the question as to the extent to which hypothetical future decisions on the establishment of purposes toward the practical implementation of projects considered can have consequences for present-day manned space flight. What actions concerning manned space flight are required today so that such projects can at all be implemented in the future or so that they may then represent a possible action alternative? This way of putting the question points to a known argument that is cited again and again in support of manned space flight: "keeping options open."

The investigation here uses several scenarios pertaining to the use of manned space flight. These scenarios above all depend on the practical implementation time frames for the large-scale projects under consideration, on the available equipment and the particular required effort. They start with the hypothetical definition of the above-analyzed project purposes and with a future decision as to their practical implementation through these projects. From this point of departure, a conclusion is then drawn in the future as to present-day action possibilities or action necessities. In this sense, in other words, target-oriented normative prognoses are set up in the form of scenarios.

Beyond that, the various European cooperation models are discussed as possibilities for action with a view to the project purposes but also regarding contributions to trans-utilitarian purposes.

Furthermore, an attempt is made to blend the detailed analyses of the various future projects into an overall evaluation. The high technical requirements and the long practical implementation time frames—beyond which prognosis of the traditional (trend-extrapolating) type are hopeless—make it quite obvious to advance the argument of "keeping options open." Here is why: requirements for the attainment of practical purposes by means of manned space flight—which crop up on short notice—presuppose the operational availability of a fundamental capacity. Beyond that, however, one must also investigate to what extent present-day manned-space-flight projects can already justify these projects.

6. THESES ON THE FUTURE OF MANNED SPACE FLIGHT

At this point, we would like briefly to formulate some theses on the future of manned space flight in the form of a perspective summary of some results.

a)A purely utilitarian justification cannot be expected presently, nor in the foreseeable future—regardless of individual activities in that direction (for example, INTELSAT recovery) whose economy, however, is disputed.

b)The system-engineering justification is presently on the defensive due to increasing automation and new remote-operation possibilities.

c)It can gain new relevance only if larger space flight purposes are tackled (SEI, SPS, etc.), which in turn would generate novel tasks, perhaps, the assembly of complex orbital infrastructures.

d)Regardless of whether one does or does not want to pursue manned space flight, it will depend heavily on trans-utilitarian purposes also in the future, as it has already in the past.

e)The "international cooperation" purpose, perhaps in conjunction with SEI, could turn out to be a workhorse here.

f)Cooperation possibilities will also become more important from the utilitarian aspect, specifically, in terms of resources clustering. In view of empty exchequers, it will hardly be possible to point up the need for any expensive parallel or multiple development efforts.

g)For Europe, in particular, new and highly promising possibilities are opening up for cooperation with the CIS countries.

h)Trans-utilitarian purposes point to social developments. New developments therefore can also have consequences in terms of generating new trans-utilitarian purposes to which manned space flight could contribute.

i)In view of urgent present-day problems in other fields, however, one must not overestimate the potential of trans-utilitarian purposes. In times of crisis, societies quite understandably are inclined to use their resources for those projects that yield a direct benefit.

j)Justifying manned space flight is a rather complex undertaking. There does not seem to be "the" purpose that could once and for all resolve the problem complex relating to justification. Instead, it is always necessary to list a large number of purposes, all of which—taken by themselves—cannot supply justification.

k)The complexity of the discourse on manned space flight, on the one hand, makes rational discourse more difficult; but, at the same time, it is all the more demanding of it, on the other hand. This dilemma in space flight discussion would appear to be beyond resolution. There cannot be any simplifications in this connection.

l)In view of this problem complex, the proponents of manned space flight still face the challenge of justifying space flight in terms of purposes in a form that can be communicated to the public.

The justification of manned space flight proved to be a complex undertaking that will not put up with any simple solutions (be they pro or con). It is precisely the trans-utilitarian purposes that generate complexity because they tie in with specific societal constellations in manifold ways. Therefore, there cannot be any justified abstract justification of manned space flight (by the same token, however, there cannot be any abstract rejection); instead, this justification must be provided in specific societal situations by means of rational discourse.

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Germany: Technology Development During Manned Space Flight

Simulation Supported Error Diagnosis for Space Applications

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[Article by Frank Plassmeier, Dr. Reimund Kueke, Dr. Dieter Exner, Kurt-Franklin Lehmann: "Simulation-Based Error Diagnosis for Space Applications"]

[Text]

OVERVIEW

This contribution describes the SIMEX (Simulation-based Expert System Tool) which employs knowledge—contained in simulation models—on causal and functional interrelationships in technical systems for the purpose of recognizing and isolating errors.

The system is designed to improve ground-based mission monitoring and to facilitate faster and more accurate localization in case an error appears.

The article explains the general concept behind the SIMEX system, the model information needed, and the diagnosis procedure. The system's development state and comparable approaches are described briefly.

1. INTRODUCTION

The telemetry data from space vehicles (for example, satellites) generally consist of measurement values (for example, temperature and pressure values) and status reports (for example, switch positions) (1). Some space vehicles, moreover, transmit error reports (exception messages) (2) such as, for example, when boundary values are exceeded. These data normally do not as yet permit a direct conclusion as to the actual cause of the error. The telemetry data are presently analyzed on the basis of procedures spelled out in writing, also encompassing the recognition and isolation of errors.

In connection with this task, it is desirable to support operating personnel by means of computer systems so as to lower operating costs and to increase the availability of space vehicles. To achieve the most efficient possible

acquisition of the knowledge required for the interpretation of telemetry data and to avoid duplication of effort, it does indeed make sense to tie this task in with other development activities and to use existing sources of knowledge. Here, one might particularly look at simulation models that contain a functional description of the components of a space vehicle and their mutual interdependences. When these data are extracted from the simulation models and when they are possibly supplemented, one already has available a considerable part of the knowledge required for FDIR (Fault Detection Isolation and Recovery).

Moreover, this approach facilitates the utilization of existing software systems for FDIR purposes; that reduces the development effort and one can therefore avoid a further increase in the number of software tools employed during the development phase.

The use of simulation models for FDIR purposes and integration with a simulation system makes it necessary for this simulation system to have clearly defined software interfaces and to permit the extraction of required model information.

2. DESCRIPTION OF SIMEX SYSTEM

The CSS (Core Simulator Software) simulation system is being developed in the context of the COLUMBUS Project; the CSS is built up in a modular fashion and has well-defined software interfaces. One essential component of this system is MDE (Model Development Environment) which supports the extraction of model data to a considerable degree. SIMEX should therefore be integrated into this simulation environment.

The system concept will be described in the next chapter. Then we will explain how the application for FDIR purposes can be supported by the suitable modeling of a technical system. After that, we describe how this information is used to generate error hypotheses.

2.1. System Concepts

The SIMEX system pursues a generate-and-test strategy consisting of three steps: first of all, the results of simulation runs—which are parametrized for an error-free system—are compared to the incoming telemetry data. Deviations between telemetry and simulation data point to the presence of an error. This step is supported in some space vehicles by the fact that error messages are telemetrized when boundary values are exceeded. In the next step—if there are any references to the presence of an error—the dependence descriptions, extracted from the simulation models, are used to generate hypotheses on possible errors that are described as model parameters. In the third step, these model parameters are checked out by comparing the telemetry data to the results of renewed simulation runs that are parametrized according to the error hypotheses.

The implementation of this strategy necessitates two interfaces between SIMEX and the simulation environment. On the one hand, an interface is needed to the MDE model development environment in order to extract the dependence descriptions from the simulation models; on the other hand, an interface is needed to the CSS running time system in order to start simulation runs with suitable parametrizing and to be able to fall back to the simulation results.

Both interfaces can be put up with the help of existing CSS or MDE interfaces that employ standard UNIX mechanisms and support a heterogeneous, distributed system architecture. For the extraction of the dependence descriptions, one can use the CTG (Code and Table Generation) interface of the MDE; for communication with the running time system, one can use the MOCS (Model Observation and Control System) interface of the running time core (see Figure 1).

2.2. Required Model Information

To be able to generate error hypotheses, it is necessary to extract, from the simulation model, information on possible errors and on the causal and functional dependencies within the model system. Moreover, it is necessary to make this information as comprehensive and detailed as possible so as to ensure efficient generation of error hypotheses and, in particular, to avoid the generation of false hypotheses as much as possible, so as to limit the number of required test runs.

MDE supplies a graphic modeling language (4) (see Figure 2) that makes it possible to describe a system with the help of functional blocks and parameters. This breakdown and the causal dependencies among the functional blocks, as well as between functional blocks and parameters, can be extracted from the model.

Besides, the activation of the input variables of functional blocks can be determined and used to determine the propagation of value changes. The functional description of the functional blocks, as such, on the other hand, cannot be used directly because it is not present in a declarative form, but instead consists of procedural code. The concept of referenced functional blocks, however, makes it possible to ascertain whether functional blocks are identical in terms of their performance. The anticipated expansion of MDE with a documentation component furthermore offers the possibility of specifying additional data on the performance of the functional blocks which can then by used by the SIMEX system.

With the help of these data, one can considerably reduce the number of hypotheses generated by tracking the causal dependences back. For example, one can use the activation mode to rule out hypotheses as to blocked switches if no switching action is expected for those switches. Data on functional symmetry deriving from identical performance of functional blocks can be used to rule out common predecessors of two functional blocks whose behavior is identical if, out of these two, only one

is tied to a deviation between observed telemetry data and simulation results. Additional data on the behavior of a functional block, for example, can be used right away to rule out redundant components of a space vehicle as error candidates.

MDE is a model development tool that offers the user considerable freedom in making up simulation models. Making simulation models that are to be used also for FDIR purposes means that one must comply with certain guidelines (5) in order to supply the required model data. In addition to modeling component states as parameters, it is necessary to reproduce the causal dependences as accurately as possible in the model structure so as to support the generation of hypotheses. For example, one should avoid the definition of functional blocks, in which one or several input variables always act only upon one part of the output variables, because, in this way, one cannot put the really existing dependences into the model and those dependences lead to the generation of false error hypotheses.

2.3. Hypothesis Generation Method

The hypothesis generation process is started after the discovery of deviations between observed telemetry data and the results of simulation runs, assuming that the system is functioning correctly. It determines a quantity of simulation parameters, each combined with the deviations for which it might be responsible. This result represents the input for the hypothesis test process in which the received telemetry data are examined together with the results of simulation runs that were parametrized in keeping with the error hypothesis.

Hypothesis generation itself is performed in two steps: first of all, the search area is restricted in that the input variables of functional blocks can be ruled out from any further observation; these blocks have neither direct nor indirect parameters as predecessors, as well as those that can be relieved on the basis of their activation mode or by analyzing the functional symmetry. This is followed by the back-tracing of the causal dependences in a Breadth First Search process. The search area is restricted by the results of the prior step, the utilization of additional specified functional information. An additional restriction is achieved by not considering candidates that are connected with a quantity of explained deviations that represents a genuine sub-quantity of the quantity of deviations explained by another candidate. Here, candidates can be parameters or output variables of functional blocks. The search is terminated when no new candidates are found any longer.

The generation of hypotheses is based on the assumption that only one error occurs at a time, but there is a possibility of recognizing at least the presence of several errors if there is no individual parameter that can explain all observed deviations.

3. DEVELOPMENT STATE

In the following chapter, we will describe past work. Then we will present the outlook for planned activities.

3.1. Work Done

A prototype of the SIMEX system was implemented in an object-oriented fashion in Common Lisp and CLOS (Common Lisp Object System). The system contains a simple simulator that replaces the CSS running time system for testing purposes. An interactive user interface implemented in the form of CLIM (Common Lisp Interface Manager) (see Figure 3) makes it possible to conduct test runs and to display their results as well as to put out model data, such as, for example, the list of all parameters of a simulation model. An exchange format for taking over MDE data was defined.

The prototype was developed at Symbolics Workstations under Genera and was transferred to SUN Sparc Systeme unter UNIX and Allegro Common Lisp. The Transfer Effort was very small due to the use of CLOS and CLIM.

The prototype of the SIMEX system was tested successfully with the help of a model of a part of the high-frequency transmission system of a telecommunications satellite.

3.2. Planned Activities Plans call for the integration of the prototype with the CSS simulation environment by the end of 1992. This requires the implementation of interfaces to the MDE model development system and to the CSS running time system.

Moreover, the prototype is to be evaluated with the help of additional models. The use of models of EURECA (European Retrievable Carrier) subsystems is planned for this purpose.

4. RELATIONSHIP TO OTHER WORK

It is the goal of the SIMEX Project to use techniques of model-based diagnosis for ground-based FDIR systems; special emphasis is placed here on integration with other systems that are employed for system development and operation, as well as the utilization of existing sources of knowledge. In this chapter, we want to compare the approach that was selected to other systems existing in the space flight sector for FDIR tasks as well as methods of model-based technical diagnosis.

The need for stepped-up automation in the space flight sector has already led to the development of several FDIR systems of which we might mention here SHARP (Spacecraft Health Automated Reasoning Prototype) based Expert System Tool) (7), DIAMS (8) and LES (LOX Expert System) (9).

The SHARP system developed by Jet Propulsion Laboratory is used for ground-based monitoring of space probes, such as, for example, Voyager. It does not

employ any model-based setup, but instead uses procedural and rule-based processes. The acquisition of knowledge is supported by graphic tools. A similar procedure also characterizes the CONNEX system that is earmarked for on-board FDIR tasks in the context of COLUMBUS and that can recognize error cases, also if they are only partly fashioned, with the help of a similarity measure. These systems therefore demand the additional preparation of FDIR knowledge basis and do not permit any direct use of existing design data.

System models for FDIR purposes must also be made up separately for the DIAMS system that follows a model-based approach and is used as prototype for monitoring the French telecommunications satellite TELECOM 1. Something similar applies to the LES system that serves to monitor the fueling of the space shuttle with liquid oxygen and that required the definition of inverted functional descriptions for the fueling system's components.

Numerous model-based systems were developed for monitoring and diagnosis tasks outside the space flight sector. Three studies may be mentioned at this point.

The GDE (10) (General Diagnostic Engine) system solves diagnosis problems for technical instruments with the help of a conflict quantity management system (ATMS, Assumption based Truth Maintenance System). The functional dependences of the technical system must be described with the help of constraints.

A system that is based on the combined use of structural data and derived, component-oriented diagnosis rules was developed to diagnose analog circuits (11). The MIMIC system (12) is to be used for process monitoring tasks and starts with a combination of semiquantitative simulation for error discovery, structural-data-based back-tracing of causal dependences for the generation of error hypotheses, and the suspension of constraints for their testing.

But these three systems likewise call for the preparation of special models. The objective in developing the SIMEX system, on the other hand, is to achieve the best possible integration with the existing system development environment. The diagnosis procedure therefore was as much as possible adapted to the information that can be derived from simulation models. The results of conventional simulation runs were used for error detection and the hypothesis test; structural information is used mostly for hypothesis generation. Information to be specified additionally only serves to restrict the number of generated hypotheses. However, in analyzing numerical simulation results, it will also become necessary to define tolerance values because many system data can be calculated only with a limited degree of accuracy.

5. SUMMARY

SIMEX is to be a ground-based FDIR system that will facilitate knowledge acquisition and that will make for good integration with existing systems. Here, it is advantageous to use a diagnosis procedure that directly employs the description of the causal and functional dependences of a spacecraft's components; this is so because, in contrast to routine products, empirical knowledge can be used only to a limited extent. Moreover, it is important to use existing functional descriptions of spacecraft to avoid duplication of effort. Finally, the use of existing development tools offers the advantage of avoiding any further growth in the heterogeneity of the development environments for space vehicles.

The point of departure for SIMEX chosen was integration with a simulation environment that—by means of well-defined interfaces—permits access to large parts of the knowledge contained in the simulation models and that facilitates the specification of additional data via a documentation component. A combination of structure-based hypothesis generation with simulation-based error discovery and hypothesis testing was chosen as diagnosis procedure because that is best suited for the available data.

The selected integrative approach is intended to counteract the science acquisition problems that are frequently encountered in connection with the use of diagnosis systems, as well as the problems arising from the fact that the diagnosis systems are not tied in with the practical application environment.

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Germany: Technology Development During Manned Space Flight

Exotic Power Plants for Space Flight

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[Article by Th. Hauler, R. Loose, B. Schaefer: "Exotic Power Plants for Space Flight"]

[Text] This lecture presents and sketches the way in which so-called "exotic power plants" work. A distinction is made here between engines with powerful thrust that can be considered a component of launch stages, and those that go into operation from the Earth orbit.

This presentation furthermore is an overview of the broad spectrum of engines that would be outstandingly suitable for exploring the apogeal space, at least in terms of basic principle. Special attention is devoted here to electrical and solar engines and the photon power plant.

The chapter on "Solar Kites" has been taken out of this lecture and will be presented as a separate subject by Mr. U. Fabian.

I. INTRODUCTION

As we begin, it makes good sense to define the term "exotic." We use that term to refer to those power plant designs whose construction is not contradicted by any laws of physics, although their technical embodiment certainly can be graded anywhere from demanding to "currently not doable."

Of course, the term "exotic" is deliberately used in a very broad fashion. For electrical power plants, specifically using the example of the Giessen RI engine, can be construed as "not yet employed in outer space in practical terms." On the other hand, the following are definitely exotic: concepts such as the American design of the nuclear-powered "ORION" deep-space ship, the "DAEDALUS" concept of the British Royal Space Society with a fusion power plant using magnetohydrodynamic nozzle systems and, naturally, the photon power plant.

What we said earlier concerning the definition of the term "exotic" also applies to power plants with powerful thrust.

Here, the spectrum ranges from the use of standard high-pressure power plants, with the possible use of "superchemistry," all the way to the so-called LACE (Liquefied Air Cycle Engine). The motivation behind the attempt to tackle exotic power plants with powerful thrust is certainly primarily of a commercial nature. Present-day chemical rocket systems have attained 95% of the theoretical performance limit; however, the last 5% may make a single-stage space transporter practically feasible.

The interest in exotic power plants for deep space missions is of a practical nature. A standard chemical rocket attains a top speed of 30 km/sec. If one tries to visualize a journey to the nearest fixed star, for example, to Barnard's Star, that is around 5 light years away, then it would take this rocket 50,000 years to get there. A constant thrust, for example, from an RI power plant, would shorten this travel time considerably.

II. ENGINES WITH POWERFUL THRUST; LAUNCH FROM EARTH

II.1. "SUPERCHEMISTRY"

Atomic Hydrogen - The energy content of a chemical fuel is an important magnitude in its output. The other magnitude is the exhaust ejection speed. The conventional leader here is the mixture of H_2/O^2. Its energy content is 3.7 kWh/kg at a typical jet velocity amounting to a maximum of 5 km/sec.

If one were to burn a more efficient fuel in a standard power plant, then the latter's output would naturally go up. Atomic hydrogen in combination with O_2 would be such a candidate. The energy content of atomic hydrogen is 59.5 kWh/kg. Unfortunately, atomic hydrogen is unstable. That could be changed only by means of spin parallelization but for that one needs magnetic fields of up to 100 kG. Exhaust outflow speeds of 20.8 kg/sec would be possible if one were to use 100% atomic hydrogen.

Metallic Hydrogen - "Normal" hydrogen is turned into metallic hydrogen under high pressure amounting to around 2 million bar. According to publications from the 70's, the artificial synthetization of metallic hydrogen

was accomplished successfully at 269°C and a pressure of 2 million bar. In 1978, the noble gas xenon was successfully converted into a metallic phase in the United States. This was accomplished at a temperature of -241°C and at a pressure of 320 kbar.

Metallic hydrogen presumably is present in liquid form under the extreme pressure and temperature conditions (20,000°C, 12 million bar pressure) prevailing in the deeper layers of Jupiter's atmosphere. Metallic hydrogen may possibly be metastable at room temperature. At 59.5 kWh/kg, its energy content is equal to that of atomic hydrogen. If one calculates the theoretical jet speed on the basis of the energy preservation principle, then one comes up with a figure of 20.7 km/sec. Of course, one thing that has not been cleared up to this very day is how one could use this element.

OZONE and FLUORINE Instead of Oxygen - The use of fluorine (F) or ozone (O_3 as oxidator increases the energy content of the fuel in combination with LH_2 to a figure of more than 4 kWh/kg. Unfortunately, ozone is chemically not stable and it is toxic, while fluorine compounds are partly extremely environmentally harmful.

II.2. ATOMIC ENERGY

Basically, it makes no difference where the energy for the acceleration of the thrust mass comes from. Conventional power plants draw this energy from chemical reactions, such as, for example, the combustion of LH_2/LOX. Any developing thermal energy of the gases is then converted into kinetic energy via the expansion nozzle. A thermal, graphite-moderated reactor was chosen for rockets as part of the American "ROVER" Program which was aimed at developing nuclear power plants for aircraft and rockets. Hydrogen was to be heated up and was to be expanded via a Laval nozzle. A flyable version of this reactor (NERVA; Nuclear Energy Reactor for Vehicle Application) was to supply around 25 t of thrust with an output of barely 1.5 million kW and a total weight of 6.5 t. This motor was run at full capacity for around one hour in 1966. A flight experiment as third stage was planned on a SATURN V. The idea was to test the orbital nuclear launch.

All pertinent investigations were suspended in 1972. The required expenditure eliminated all advantages of such a system; besides, the exhaust ejection speeds attained were relatively low because the gas temperature was too low. It was also realized clearly at that time that it was advisable for environmental protection reasons to drop the idea of having an atomic power plant within the atmosphere.

II.3. COMBINATION POWER PLANTS

Conventional rocket power plants entail the disadvantage of having to carry the oxidator along as dead load also when there is enough air present in the atmosphere to keep the combustion going. This brings us to the development of so-called synerjet motors. So-called air-breathing engines, for example, turbojets, were used during low-altitude flight at relatively slow speeds. Ramjet power plants would be very suitable at medium speeds (starting at Mach 3.5).

When all of these power plant forms are integrated in power plant, we speak in terms of a combination power plant. Air-breathing power plants have very high exhaust ejection speeds at relatively low fuel consumption.

Here are some typical values: a normal, multi-stage rocket has already consumed 50% of the fuel mass present at launch by the end of the first stage; at that point, it has reached only one-third of the speed needed for orbiting. At the same speed, air-breathing power plants would only have consumed 10% of the fuel.

II.4. LACE (Liquefied Air Cycle Engine; "Collectors")

In order to make meaningful use of such "collectors," one starts with the assumption that the spaceship has a "rocketoid" unit, in addition to the above-mentioned component of the combination power plant. In that case, flight through the atmosphere causes the oxygen in the air to be liquefied as a result of fractionated distillation and to be fed to the oxygen tank. Such a system offers the following advantages:

1.one uses air-breathing engines with their low fuel consumption and the hydrogen that is carried along is simultaneously used as fuel for the jet engines, and

2.one can increase the payload because the oxygen supply for the rocket need not be considered as part of the launch weight.

Illustration shows a diagram of a system for liquefying the air in flight.

Illustration shows a longitudinal profile through the system used for liquefying the air in flight.

II.5. RAMJET ENGINES WITH OUTSIDE COMBUSTION

An exotic ramjet engine is sketched in the next following figure. Here one dispenses with a corresponding combustion chamber; instead, one lets the combustion take place in the outer, lower region of the vehicle. In the process, a superpressure is created which produces both lift and propulsion. One problem here has to do with the speed at which combustion must take place, because otherwise the fuel will be expelled behind the vehicle without any effect. For the moment, therefore, one can only consider LH as fuel. Here, of course, the problem springs from the low density of hydrogen.

II.6. THE ROCKET IN THE BALLOON

An original idea presented in the 20 Sep 73 issue of NEW SCIENTIST notes that conventional rockets are necessarily very plump because they consume most of their initial thrust to lift their own fuel.

A solution to this dilemma would be first to lift the fuel and, so to speak, to gas the rocket up as it flies past.

The "practical solution" consists of a long, vertical, and strong sausage balloon filled with hydrogen and oxygen. Daedalus (not to be confused with the starship), the creator of this project, calculated that a balloon with a diameter of only 1 m would be able to transfer a thrust of 1,000 t (10 g up to 8 km/sec) to a rocket. A problem, of course, here involves the necessary hose length which would have to be approximately 300 km at an "atmospheric thickness" of about 50 km. One way out would be to position the hose obliquely (10°); that would simultaneously necessitate only a minor thrust vector change to reach the orbit. Here is how this would work: Separated by a membrane, there are areas in the lower part of the hose for both gases that burn off at suitable speed; this facilitates the thorough mixing of the gases with subsequent ignition. The speed range above the free burn rate of a hydrogen-oxygen mixture amounting to about 3,000 m/sec means that no partition is needed and ignition takes place by means of a laser on-board the rocket.

Here it is interesting to note that the same principle could also be used for the purpose of braking out of the orbit; but that would seem to require a "high degree of navigational accuracy" because one must after all thread oneself into the balloon.

III. POWER PLANTS WITH LOW THRUST, LAUNCH FROM EARTH ORBIT

III.1. ANTECEDENTS

The advantage deriving from conventional, chemical rocket power plant—in terms of delivering a sufficiently powerful thrust to overcome the Earth's gravity—decisively shaped the progress of space flight. In the process, it was necessary to accept disadvantages such as the large fuel consumption and the resultant lower efficiency, plus a smaller payload.

The situation in space is utterly different: For the most part, there is no gravity connected with celestial bodies and the approximate vacuum makes it possible to use other drive mechanisms. The long distances that will have to be covered by unmanned or subsequently manned vehicles on their way to other planets, planetoids, or comets mean that one cannot possibly use chemical drives for reasons of weight or time.

The possibility of swing-by maneuvers is heavily curtailed by the dependence on planet constellations. In 1906, the American rocket pioneer Robert Goddard for the first time considered electrically-charged particles to drive rockets. Hermann Oberth developed the first concrete concepts in his book entitled "Wege zur Raumschiffahrt" [Roads to Space Travel] in 1929.

III.2. HOW ELECTRICAL ENGINES WORK

Electrical engines basically work in a manner similar to chemical engines. Here again, a drive jet is generated and its reaction accelerates the spaceship. The generation of the jet, however, is not based on combustion but rather on the supply of electrical energy. Consequently, no combustion gases are expelled; instead, there is a plasma or ion jet.

This exotic type of engine is distinguished by high jet ejection speeds, a high overall efficiency, low fuel consumption, and a high payload. Of course, they have small thrust, which makes them unfit for use in the Earth's atmosphere, and they need their own energy supply. This will be touched on briefly at the end.

III.3.STRUCTURE AND OPERATING PROCEDURE

Electrical drives can be subdivided into three classes in accordance with the manner of acceleration of the drive mass: electrochemical, electromagnetic, and electrostatic drives. I would like briefly to sketch these three drives and I would like then to go into somewhat greater detail regarding the method that is most likely to be used in the near future.

III.3.1. Electrothermal Drives

The basic principle behind electrothermal drives rests on the fact that gases expand or raise the pressure as they are heated up and that they are thus able to perform work. The gaseous fuels of the electrothermal drives, such as hydrogen or ammonia, can be heated in three different ways:

- By means of the Joule effect heat of ohmic resistance elements that have current flowing through them (see Fig. 4), one can alter the thrust and the exhaust flow speed of the gases within a broad range. Such drives can thus be used as maneuvering or steering units. Of course, there are temperature limits on the materials involved in the elements.
- A light arc between an axial cathode and the nozzle wall as anode heats the gas which flows in, in between, in such a manner that one gets a thermal plasma which is expanded through the nozzle. Many different disadvantages and problems—such as electrode corrosion and light-arc instability—heavily restrict its use in space travel. But electrothermal drives are used in practice as a high-speed plasma source in wind tunnels and generate temperatures of up to 22,000 K.
- Bombarding a heat exchanger pipe with electrons—for the purpose of heating it up combines the disadvantages of the ohmic resistance and light-arc heating without offering their advantages. This method does not make sense.

Test results:

	Ohmic Resistance	Light Arc
Electrical input power	30 kW	30 kW
Exhaust ejection speed	8.4 km/s	10-20 km/sec
Overall efficiency	67%	approximately 55%

General disadvantages consist of a partly lower efficiency during the conversion of electrical energy into thermal energy, plus a short heat-up time of the gas due to the latter's speed. H_2O_2, hydrazine, and Cavea B ($C_9H_{20}N_4O_6$) were tested in addition to the light gases H_2 and NH_3.

III.3.2. Electromagnetic Drives

The driving medium, that is to say, hydrogen, is ionized and is then accelerated in electrical and magnetic fields (Coulomb or Lorentz forces). Here, we distinguish two types:

- Continual electromagnetic drives are so structured that the forces of electron and magnetic fields constantly accelerate the ions. In so-called Hallstrom accelerators (Fig. 5), the ions first are imparted speed by virtue of the radially aligned electrical field in order then to be driven axially out of the nozzle by the Lorentz force.
- Discontinuous electromagnetic drives partly employ a condenser discharge for ionization. A surrounding magnetic field forces the free electrons in the plasma to travel along circular paths, as a result of which the residual gas is ionized. The magnetic field generated by the current surge heats the plasma up highly and accelerates it to about 200 km/sec.

Electromagnetic drives encounter problems in connection with jet neutralization—the spaceship would again brake itself with an electrically charged jet—and in connection with the electrode corrosion of systems that are not without electrodes. The exhaust speeds and the thrust accelerations attain only theoretical values.

III.3.3. Electrostatic Drives

Electrostatic drives are highly promising and they will also be treated somewhat in greater detail. They work with ionized metal vapors, mostly alkali metals with a low ionization energy that are accelerated in electrical high-voltage fields. They consist of three essential parts: an ion source—the basic differentiation feature—plus an electrostatic accelerator and a neutralizer.

III.3.3.1. Surface of Contact Ion Sources

They generate electrically-charged particles through the reciprocal interaction of mostly cesium vapors with hot metallic surfaces, preferably porous tungsten. The ionization energy of the metal vapor must be below the electron outlet work of the surface material and its melting point must be above the operating temperature 1,400-1,500 K. In our case, the energies are 3.87 eV (Cs) and 4.38 eV (W).

Fig. 6 shows a diagram. The cesium is vaporized by means of electrical heating (1) and is piped into the chamber in front of the ionizer in a dosed manner (2). There the steam is diffused through the pores of the hot tungsten (50; in the process, the outside electrons of the cesium absorb the tungsten's thermal energy and can be separated from the bond. The cesium ions that result from this effect of contact ionization are now accelerated (6) and are neutralized by the electrons that flow in (9, 10). The braking electrode builds up an electrical barrier between the neutralized jet and the emitter so that neutralization does not take place already prior to acceleration. Using this method, one can attain high flow densities and high ionization efficiencies with relatively low input energy.

III.3.3.2. Gas Discharge Ion Sources

They also work with vapors of heavy atoms, mostly cesium or also mercury; but basically—in contrast to the contact ion source—they make it possible to use all vaporizable substances. The two most important types—the Kaufman ion source and the high-frequency ion source—both generate plasma and form ions by applying an electrical field; both generate a high-density ion beam that is limited in terms of space. They are distinguished by virtue of the plasma formation process, the geometry of the outlet opening, and the use of outer magnetic fields.

a) The Kaufman ion source (Fig. 7) works according to the following basic principle: a heated cathode acts as the electron emitter. Its thermal electrons ionize the vapor flowing through the inlet opening by surges. The resultant plasma is expanded up to the inner chamber wall which is poled as anode. The ions are accelerated by means of a negative electrode and the jet is neutralized subsequently. The outer magnetic field holds the emitted electrons inside the ionization chamber and thus increases the distance and also the surge probability of the electrons. Together with the following system, this system is the most promising in terms of practical use.

b) There is a great potential for practical use of high-frequency ion sources in drives with a smaller output, such as they are needed to adjust the position of space vehicles. One of the system's great advantages consists of plasma formation by means of electrode-less high-frequency discharge; in contrast to other electrostatic drives, this makes for a long service life. Fig. 5 is a diagram illustrating the structure of this unit: The discharge vessel is inside a coil that generates a high-frequency electrical rotational field there. This accelerates the electrons and ions in the drive gas which are always present on account of thermal or external excitation; as a result, neutral gas atoms are ionized as a result. These ions are then accelerated by two corresponding electrodes (6 and 8).

The development of a "radio-frequency-ionization power plant" (RIT) under the direction of H. Loeb at the University of Giessen is highly promising. Its first use was planned on the TV-Sat 1 satellite but the undertaking had to be abandoned in 1980 due to a shortage of funds. Now, the European space platform EURECA is to be equipped with the first model, the RIT 10; it is to fly or it is supposed to have been flow this year (Fig. 8). At

an exhaust outflow speed of 31 km/sec, 80% fuel consumption, and 10,000 hours of service life, RIT 10 attains a thrust of 10 mN. During that time, it consumed precisely 11.5 kg of fuel during a long-term test. You can get additional data on RIT 10 and its follow-on model, RIT 35L, from Table 1.

Here are two more examples for illustration purposes: Using six RIT 10 to stabilize the position of a geostationary satellite, one would require 46.7 kg of fuel and an average burn time of barely one month per engine over 10 years of service life. For energy supply (see below), one would need an additional solar cell surface of 4 m^2; that would correspond to a weight of 18 kg; compared to a satellite of 1-1.5 t, that amounts to hardly anything.

III.4. ENERGY SUPPLY

There is a possibility of using solar cells and that would be sufficient for near-Earth satellites. Interplanetary missions outside the planetoid belt must draw the energy for their power plants from small reactors. The latter's weight-output ratio however currently still leaves much to be desired.

III.5. Outlook

In other words, the future looks good for electrical drives. Position adjustment of apogeal satellites, platforms, and space stations is just one area of practical use. Following the VOYAGER 2 mission, there is a desire now for more profound discoveries concerning our solar system, not to mention the urge to reach the remote stars. Of course, considering a flying time of between 4,000 and 5,000 years, not even electrical drives will help make that wish come true.

IV. SYSTEMS FOR DEEP SPACE FLIGHT WITH POWERFUL THRUST

Preliminary designs for manned spaceships that would be suitable for interstellar flights exist already today. Here we might mention the Orion and Daedalus projects whose value resides in the effort to show what difficulties will have to be overcome on the way to "their" practical implementation. They furthermore tell us the limit of what we can accomplish at all, considering the knowledge contained in our present-day physics. But conducting these studies, at this point in time, is by no means useless because they constitute the necessary spade work on the long road to practical implementation; if these studies were not done, the moment of the first interstellar flight would be pushed even further into the future.

IV.1. DAEDALUS PROJECT

This two-stage concept is a study by the British Interplanetary Society conducted under the direction of Allan Bond. The idea for this kind of power plant, among other things, comes from Professor F. Winterberg, who had expected that an experimental version would be ready as early as 1985.

Nuclear fusion is the basis of this power plant. Small fuel balls are heavily compressed by radiation so that conditions for ignition are obtained. Some pellet compounds are available as fusion fuel, for example (i) deuterium/deuterium, (ii) deuterium/tritium (the simplest ignition conditions), or (iii) helium-3/deuterium, which would be the ideal composition.

The two parameters are a) the highest possible heat generation from primary energy and b) the smallest possible flow of energy-rich neutrons which are to make for a high degree of efficiency and small shielding.

For deuterium/deuterium, the corresponding values are (a: 30%; b: 50%), for deuterium/tritium (a: 15%; b: 75%), and for helium-3/deuterium (a: 58%; b: 2%). The use of the tritium pellet is not advisable also because of its half-life which is 12 years; that would make its use appear rather doubtful at least for longer missions. One disadvantage of the helium-3 pellet is the fact that helium-3 is rather in short supply. This problem could be solved by industrial procurement of helium-3 from the Jupiter atmosphere.

The pellets probably consist of a deuterium-honeycomb structure and a filling of helium-3 weighing 2.85 or 0.29 g and which have a supraconducting surface for injection into the combustion chamber. The electrical energy (13 MW(e)) is obtained from the charged, hot plasma by means of an MHD converter that is integrated into the nozzle.

The Daedalus mission to Barnard's Star could look something like this: Daedalus is launched from a parking orbit with an initial weight of 54,056 t. The first stage consumed its fuel after 2.05 years and, following separation, the second stages burns for another 1.76 year. After those 3.81 years, the vehicle has attained a speed 36,300 km/sec, about 12.1% of the speed of light, at a distance of 0.21 light-year. After another 47.1 years, Daedalus arrives at Barnard's Star, and while flying through, gathers scientific data that are sent back to Earth.

IV.2. ORION

In the case of Project Orion, we, so to speak "are riding" on exploding hydrogen bombs. Technically speaking, this is the "least" demanding of the projects presented. It was investigated intensively in theoretical and experimental terms between 1960 and 1965 and it was finally discontinued on account of the ban on setting off nuclear weapons in space.

This involves firing atomic bombs—with a thrust source (pulse units) at a rate of one pulse per second—through a tube extending through the pressure plate. Behind the vehicle, the pulse unit is made to detonate and the remnants of the evaporated pulse unit impact the pressure plate which gains thrust as a result. One can achieve considerable performance figures by using nuclear shaped charges that produce a directed explosion.

IV.3. THE PHOTON ROCKET

The largest amount of energy can be obtained from the matter-energy equivalence ($E = mc^2$)25 billion kWh/kg of matter. The only way to get there is via the annihilation of matter with antimatter. Here, the energy is released in each case in the form of highly-energetic gamma quantums that move at an angle of 160° with respect to each other, and of course, at the speed of light. One could use it as the power plant for a spaceship if it were possible to build a reflector for this kind of radiation.

So much for the difficulties that cannot be overcome at this point in time. First of all, antimatter is available in a quantity that cannot be weighed and would also be extremely difficult to use, because on contact with matter of which our world is made up, it would immediate annihilate it.

The other problem consists of the fact that the reflectors are just not available. If all of these problems were to be solved, we would have the best possible interstellar ship in the form of the photon rocket that would at all be possible on the basis of our physics. Speeds close to the speed of light would be possible with that spaceship. Of course, one cannot see any way to make this photon power plant at this point.

V. INTERSTELLAR FLIGHT

At this point, we might recall once again that this lecture relates to concepts and ideas that do not conflict with physics, such as it is right now, or that point up possibilities in the area of physical laws that have not yet been clarified. The technology and engineering needed for practical implementation are mostly unknown and perhaps they can never be developed. The motivation here is to set the physical framework of the theoretical possibilities. The most important premise is the impossibility of getting trans-light velocity ("Exceptions," see below). In combination with time dilation as one approaches the speed of light, this means that even with the "ideal" rocket equipped with a photon power plant on the basis of the matter-antimatter annihilation, one can achieve only an action radius of about 10 light years if the spaceship is to return to Earth within about 30 Earth-years; here, the maximum speed is "only" about 70% of the speed of light. Of course, if one forgets about a return within a justifiable time span, then, using this power plant, it would be possible to circle the known universe within about 56 on-board years, while many billions of years would have gone by on Earth, which would no longer be in existence.

Here is an overview of "possible" forms of power plants:

- chemical power plants; maximum speed about 30 km/sec (1/10,000 of the speed of light);
- using solar wind, solar kites; slow speed, usable only within the internal reaches of the solar system;
- fission drives (nuclear fission); energy essential does not come from mass defect but rather from electrical rejection of nucleus fractions; maximum speed about 0.3% the speed of light;
- gravitation maneuvers; practiced somewhat more frequently already in the solar system; a swing-by would be ideal here with a double-star system of two white dwarves that circle each other at a distance of 1 million km; maximum speed about 1% of the speed of light;
- electrical and magnetic fields in space; they are too weak to generate any worthwhile propulsion but they could be used for direction changes during long journeys;
- fusion; attainable exhaust flow speeds in case of hydrogen fusion into helium, 37,200 km/sec from energy yield corresponding to 12.4% the speed of light; two promising research directions at this point in time.
- (i)Tokamak concept: Enclosing the hot plasma (100,000 million degrees(?)!) in a magnetic field for stationary energy procurement on Earth is conceivable; but this is rather unlikely as propulsion for a starship because of the low matter density; (ii) ignition (compression until attainment of ignition conditions) of fuel pellets (for example, frozen hydrogen pellets) by means of laser or particle beam. Three concepts based on fusion are presented below;
- annihilation of matter-antimatter; $E = mc^2$, physically strongest energy source, complete conversion of mass into energy, so far not observed in weighable quantities because antimatter is difficult to obtain; Problem: one gets too high-energy gamma quantums at an angle of 180°, and in our present-day physics, there is no "reflector" for this radiation;
- black holes; typically, 10% of the mass are converted into energy when matter plunges into a black hole assuming the existence of "mini-black holes" and their "easy handling," one gets an energy source stronger than fusion;
- Einstein-Rosen bridges, worm holes; assumption that matter that gets into a black hole again comes out of a white hole someplace else in the universe; worm holes "are" so to speak short-cut connections between two points of our four-dimensional space-time; here, the space between the points is heavily curved by a big mass and that is a hypothetical consequence of the quantum theory of gravitation; a spaceship flying this shorter "route" would have covered a distance in the eyes of a resting observer that is greater than the distance covered by light during the flying time—although that spaceship never flew at superluminal speed; all of this is highly speculative;
- tachions; the theory of relativity simply prohibits the transition from subluminal speed to superluminal speed, but not permanent existence in the range of superluminal speed; hypothetical particles—the tachions which do precisely that—have been suggested; if they exist and if they interact with our world (only then would it be possible to evidence them), one could, of course, not use them as a power plant concept but they might possibly be helpful in information transfer.

Let us quote Professor Doctor F. Winterberg at this point on yet another hypothetical possibility of spacecraft power plants (from "Die grenzenlose Dimension" [The Boundless Dimension], H. Ruppe):

"Perhaps one could use the tremendous energy,which is released during hypothetical proton fission at extreme magnetic field intensities, to drive space vehicles without radiation problems when antimatter is used.

"But I believe that another possibility is much more interesting. If it should turn out indeed that, first of all, the monopoles (assuming the magnetic property of the quark, author's footnote) have a negative mass and, second, that the monopoles can be produced in large quantities, then this would have inestimable technical consequences. The mass production of monopoles could perhaps be accomplished with monopoles themselves. If one has only a few monopoles, then one could simply fire the monopoles at matter by virtue of their acceleration to maximum energies in static magnetic fields and one could thus knock more monopoles out of the protons; this would lead to a chain-reaction-like proliferation of the monopoles.

"Now, if one has enough monopoles, then one could firmly build them into the crystal lattice of a solid body. On account of their much stronger magnetic reciprocal effect and because of their much greater, although negative mass, that could lead to a body with a strength that would be, for example, 10,000 times greater than steel and with a melting point of several millions of degrees. Entirely novel nuclear rocket power plants could be designed with such ultra-strong raw materials.

"But there is yet another, quite revolutionary possibility. If the mass of the monopoles is negative, then—by building monopoles into a solid having a positive mass—one could get close to a material state in which the resting mass disappears. That would apply equally to living as well as lifeless matter. Let us apply this to a space vehicle: in that way, one could not only reduce the energy requirement for interstellar journeys, but one could even implement relativistic space flight. If it should be possible to move a spaceship as close as desired to the state of the vanishing resting mass, then that spaceship could in this material state approach the speed of light as much as desired. The energy needed for that, by the way, would not be very great. A flashlight, for example, accelerates a photon with a zero resting mass with very little energy quite momentarily to the speed of light. According to the theory of relativity, the travel time measured for photons in their internal system is zero, even to the remotest spiral nebula. For example, a travel time of one month to the star Alpha Centauri would be conceivable for a macroscopic body with almost vanishing resting mass.

"If the predicted material states of just about vanishing resting mass should actually exist and if a galactic civilization should have seized them a long time ago, then this civilization could exist in interstellar space, relieved of the compulsion to live on the surfaces of planets. Perhaps, there is such a civilization and perhaps it has been observing us from its inertial spaceships for thousands of years already. But perhaps all of these speculations are wrong, and the higher civilizations developed into a state that can simply no longer be defined with pure laws of physics and that would appear as puzzling to us as perhaps color television was to Plato (end of quotation)."

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BIOBOX on BION-10

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[Article by Dr. P. Kern, Dr. W. Scheller, V. Strobel, M. Fehrenbach, A. Vogelei, Dornier GmbH, Friedrichshafen: "BIOBOX on BION-10"]

[Text]

OVERVIEW

The BIOBOX program comprises a payload development that generally offers a modular infrastructure to carry out bio-science experiments. The particular experimental configuration is especially adapted to the problem. The BIOBOX program is presented in detail below. New solution approaches had to be found due to the experimental requirements and the operational concept to which we were not accustomed. The first BIOBOX flight is scheduled for December 1992 on a Russian return capsule of the BION type as part of the BION-10 mission.

The "development of a BIOBOX" contract was carried out under ESTEC Contract Number 9636/91/N:/JS.

1. REQUIREMENTS

BIOBOX (Fig. 1) is a multi-user unit that offers a standardized infrastructure for the performance of a large number of biological experiments under µg conditions. BIOBOX consists of an incubator part and an electronics part. The incubator contains the experiments and offers the necessary environmental conditions, such as freely-programmable temperature profiles in the range from 4°C to 37°C (+/- 0.5°C) and monitoring the inside atmosphere. In contrast to all other similar payloads for Spacelab (for example, BIORACK, BIOLABOR, etc.), BIOBOX for the first time offers the possibility of complete, continually monitoring and recording of environmental conditions throughout the entire mission starting with the insertion of the experiments in BIOBOX in the laboratory during all shipments through the space flight all the way to the return into the laboratory.

BIOBOX does not have any fixed experimental configuration. It is based on the use of experiment containers—already developed by ESA—from the BIORACK and the CIS (Cells In Space auf Maser) program, as well as new, specific experimental cells. A 1xg reference centrifuge is a firm component of the infrastructure for bio-science experiments.

The 1xg reference centrifuge is a key element because, from the biological viewpoint, primarily two parameters are definitely altered during a space flight, that is to say, the absent gravity and the increased radiation. Two groups of in-flight experiments were carried out in order to be able clearly to match up the cause of the discovered biological changes:

1) static experiments

- g-conditions
- increased radiation load

2) dynamic experiments

- 1xg condition with quasi-"Earth acceleration" on a centrifuge
- increased radiation load.

The results of the in-flight experiments will be compared later on with identical reference experiments on Earth, synchronized in terms of time (1xg condition, "normal" radiation load).

2. AREAS OF USE

The objective of the first mission is to investigate the behavior of bone cells under µg conditions. Bone cells from all developmental stages are used in order to be able to subject the mineralization and resorption processes more exactly.

These investigations are of interest particularly for long-time flights because there is a massive decomposition of bone substance here due to the absent mechanical stress.

Moreover, BIOBOX offers the possibility of performing other types of experiments, for example:

- Plant experiments

- gravitation biology: behavior of plants under weightlessness; is there a "gravity sensor" and how does it work?
- genetic stability
- change in metabolism: knowledge on possible changes of photosynthesis output is of particular significance to the use of plants in regenerative, biological life preservation systems.

- Cell biology as foundation for biotechnology in outer space

- Protein crystallization

- Fluid science experiments.

3. SYSTEM STRUCTURE

3.1. Subsystems

3.1.1. Structure

The mechanical concept of BIOBOX consists of a basic framework that holds all loads, that carries the experimental platform, a d that also represents the mechanical interface to the satellite. This is an improvement of the Dornier concept that was used for the first time for the

BIOLABOR incubators in the D2 mission. The incubator housing has a purely thermal function and is built as a non-load-bearing sandwich construction that is attached to the basic frame. The incubator is in the experimental platform with the experimental containers (μg experiments) and the modified 1xg reference centrifuge for the dynamic experiments. The centrifuge was originally developed by Dornier for ESA's BIORACK.

3.1.2. Thermal Control

Active thermal control is accomplished by means of two thermal assemblies that consist of Peltier elements and bilateral air heat exchangers. Inside and outside, fans generate a forced countercurrent convection to improve the heat transport.

3.1.3. Electronics

The electronics part (Fig. 4) consists of the facility controller and the centrifuge electronics. The facility controller contains all electrical interfaces to the BION satellite:

- Power, priority-controlled selection from three channels

- 4 remote command channels, digital

- TK1: "Start Experiment"
- TK2: "Stop Experiment"
- TK3: "Emergency Shutdown"
- TK4: Trigger for "Transmit Telemetry packet"

- 1 telemetry channel, analog-coded data packet with 15 channels for HK and experimental data.

Because the basic design of the satellite is more than 20 years old, the capacity of the telemetry channels is also limited. The scanning frequency for the telemetry signal is about 0.5-1 Hz.

The facility controller is based on a commercial 8-bit microcontroller, MIL-type, DC/DC converters and programmable gate arrays. Here are its functions:

- Control of BIOBOX

- temperature program
- experimental program

- Temperature regulation

- Data recording and storage

- internal equipment data (HK data)
- experimental data
- operation of remote commands and telemetry channel.

The facility controller offers a plurality of external interfaces (see Chapter 3.4 for details). The occupation of the experimental data channels can be freely selected according to the configuration of the experiment. The other channels are used for controlling BIOBOX.

3.2. Experimental Equipment

3.2.1. 1xg Reference Centrifuge

The 1xg reference centrifuge is based on the mechanics of the BIORACK centrifuge. The main difference with respect to BIORACK consists of the fact that in BIOBOX the centrifuge is always charged. Besides, the connection output of the centrifuge motor was limited to 2 W. To prevent any mechanical damage to the bearings, the centrifuge is equipped with a locking mechanism that relieves the bearings during launch and landing. This mechanism is tightened by a circulating Kevlar tape. The tape is unreeled from a roll electromechanically to unlock the centrifuge. There is a redundant unlocking system on account of the great scientific importance of the 1xg reference experiments. The centrifuge is locked again by winding the tape up prior to landing. Figure 5 shows the accommodation of the experimental equipment in BIOBOX.

The digital centrifuge electronics are a new development especially designed for BIOBOX. They regulate the centrifuge acceleration at 1xg +/- 1% as well as the launch and stop profile. The centrifuge electronics are controlled by the facility controller by means of commands and send the HK data back.

3.2.2. Hardware Experiment

The experimental configuration for BIOBOX on BION 10 consists of the following:

- 3x CIS experiment container with 8 plunger units each for the static experiments,
- 6x BIORACK type IE container with 1 plunger unit each on centrifuge for reference experiments.

The plunger units contain the actual biological experiment. They consist of a system of communicating tubes. The individual experiment steps can be performed in a volume-neutral manner by means of the controlled shifting of internal pistons.

The experiment containers on the centrifuge form two groups with three experiments each. They are controlled in each case by a separate controller (switch and control box, SCB).

The CIS containers also hold their own experiment controller in each case.

The facility controller starts the experiments. During operation, it accepts permanent HK and experimental data from the CIS containers and the two SCBs and monitors the status of the experiment.

3.3. Software and Redundances

Control is accomplished primarily by a specifically experiment-tailored, timed procedural program that is influenced by remote commands. The monitoring of the BIOBOX with temperature regulation, data recording

and storage completely covers the entire time span from loading BIOBOX in the laboratory all the way to after the landing.

Nominally, the experiment time line is started directly after the separation of the capsule from the third rocket stage by the command TK1. To ensure the experiment's success, a missing "TK1" however can also be replaced by three independent, internal trigger sources, such as detection as of "start of μg condition" or two independent time-outs. This means that BIOBOX can also operate in a completely autarchic manner which definitely increases the probability of mission success.

The command TK1 "start experiment" means that the centrifuge is unlocked and started. At the same time, the temperature is raised to 37°C and the experiments commenced.

The command TK2 terminates the experimental phase. The centrifuge is stopped and locked and the incubator temperature is lowered to storage temperature.

If there is no TK2 "experiment stop" command, then it can also be replaced by internal trigger sources, such as "end of μg condition" or various time-outs.

3.4. Technical Data and Interfaces

Here are the technical data for BIOBOX:

Process	80,535 microcontroller
File store	1 MByte (memory card)
Data channels	
digital inputs/outputs for experiments	32 channels, 20 channels
analog inputs for experiments	48 channels (single-ended), 30 channels
analog outputs	2 channels
Power consumption	
average/peak	30-50 W/120 W (approximately 1 hr)
Dimensions	693 x 439 x 323 mm^3 (L x B x H)
Weight	
without experiments	28 kg
with experiments	38 kg
Temperature range for experiments	4°C-37°C +/- 0.5°C
programmable as time profile	
Useful volume	23.4 l

4. PHILOSOPHY BEHIND COMPONENTS

Primary CAM components (commercial, military, avionics) are used in the BIOBOX program for the first time. For example, the facility controller is based on a commercial microcontroller; the DC/DC converters are MIL conversions; the acceleration sensor is a commercial product. Most of the active components of the facility controller are MIL 883B types. The fitness of the components was proved during the qualification program.

5. TESTS The Russian vehicle creates relatively high mechanical requirements for the payloads. The latter were checked out by means of a finite-element analysis and through the qualification test. The mechanical qualification program comprised the following tests, among others:

- Random vibration

- 8xg rms, duration 480 sec - Quasistatic load

- 20 Hz sine, 16xg, duration 60 sec - Shock tests

- Transport:
- 9xg, 5-10 msec, 2,500 shocks

- Reentry:
- 40xg, 0.5-2 msec, 10 shocks
- 100xg, 01.-2 msec, 10 shocks
- 150xg, 0.5-2 msec, 4 shocks

- Landing:
- 40xg, 5-10 msec, 5 shocks.

6. VEHICLE

The FOTON reentry capsule is of the BION type (Figs. 6 and 7); it contains the BIOBOX and is launched by means of a SOYUZ rocket from Plesetsk (approximately 800 km north of Moscow) from a polar orbit. BIOBOX is the third main payload along with two experimental units and monkeys. The BION capsule has the following properties:

Printed capsule with standard atmosphere and life preservation system	
Duration of flight	14-16 days
Orbit	
Altitude	220-330 km
Inclination	62.8°
Payload volume	4.7 m^3
Payload weight	700 kg
Electrical output	
Average	400 W
Peak	700 W (maximum 1.5 hr/day)
Temperature	15-28°C
μg quality	> 10-4xg, free drifting
Late access	up to 6 hrs prior to launch
Early retrieval	approximately 1 hr after landing

BION supplies BIOBOX in flight from the external battery (power supply container). This container is blasted off prior to landing and only the battery inside the capsule is available.

The TK1-Tk4 remote commands are given to BIOBOX by the BION satellite; this involves either:

- preprogrammed periodic commands,

- preprogrammed commands at a specific point in time, or

- indirect, intermediate-stored commands in case of radio contact, or

- direct command in case of radio contact.

The telemetry data are stored on tape onboard of BION and are transmitted to the ground station during periods with radio contact.

7. OPERATIONAL ASPECTS

Compared to the procedure for Shuttle payloads, the operational scenario of BIOBOX is completely different because the tested payload in Plesetsk is taken out prior to launch for loading with the experiments. Here is the operational procedure:

- delivery of flying model for integration and for system tests on KB FOTON to Kuibyshev/Volga (now again called Samara);
- transport of FOTON capsule by rail (2,000 km) to the Plesetsk launch site (800 km north of Moscow);
- system tests;
- extraction of BIOBOX from satellite (5 days prior to flight);
- transport to Moscow (800 km by rail);
- insertion of experiments in BIOBOX;
- return shipment to launch site (800 km by rail);
- installation of BIOBOX in FOTON and test of payload (2 days prior to flight);
- flight (mission time 14 days);
- landing in Kazakhstan;
- removal of BIOBOX and shipment back to Moscow;
- removal of experiments.

After BIOBOX has been loaded with the experiments, the temperature control, data recording and data storage go into action. During these phases, BIOBOX is supplied with energy from a portable, external battery or via the EGSE.

8. PROGRAM ASPECTS

Within the BIOBOX program, ESA is responsible for payload development while the Russians provide the opportunity for the flight. The experiments are carried out by mixed European and Russian teams.

The BIOBOX development team consists of the following firms:

- Dornier (Germany) as the main contractor * Management, System Engineering, AIT - Subcontractors: * Kayser Italia (I)

- Facility Controller with Hardware and Software, System EGSE * Verhaert Design & Development (Belgium)

- Mechanics & Incubator, MGSE * Carrar (France)

- 1xg reference centrifuge with EGSE * CCM (the Netherlands)

- CIS-Container, Plunger Units, Switch and Control Boxes and EGSE.

The C/D hardware phase began in October 1991. The delivery as such comprises the following: 1 qualification model, 1 flying model, and 1 spare flying model with the necessary ground and testing instruments. Figure 8 shows the three models prior to delivery to ESA. The experiment sequence test took place in March 1992 using the qualification model. All models were delivered to ESA, the client, in July 1992. The "BIOBOX for BION 10" program ended after the BIOBOX flight in December 1992. Plans call for continuing the BIOBOX program in terms of certain major focal points during additional missions together with CIS. BIOBOX is also suitable for use in Shuttle Middeck Locker.

Germany: Technology Development During Manned Space Flight

Applications of Virtual Cockpit in Development of Transport Aircraft

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[Text]

OVERVIEW

The complexity of the cockpit as a man-machine interface calls for using advanced development tools with which one can illustrate high-grade display formats and operating elements quickly and as realistically as possible.

This article describes the "virtual cockpit" of the German Airbus as a development tool. The following aspects are pointed up:

-A comparison of civilian and military aircraft developments over the past 30 years shows a significant technology gap in tactical military air transports whereas three aircraft generations sprang up in the civilian sector. This is why the transfer of tried and tested "civilian" technology to military applications in terms of "dual use" looks promising.

-Military transport missions establish requirements for performance such as low-level flight at night and during poor weather and visibility conditions that are partly new for transport aircraft and therefore represent a

technological challenge. The demonstration of these abilities and the assessment of the technological solution concepts demand the employment of suitable development facilities.

-In terms of its capacities, functions, and components, the "virtual cockpit" is described in the form of hardware and software. The main emphasis in the investigations currently is on the central monitoring and attendance of aircraft systems, among other things, by means of touch-sensitive multifunctional display screens. Work to make the "virtual cockpit" was promoted partly in the context of technology studies by the Federal Ministry of Research and Technology.

1. COMPARISON OF CIVILIAN AND MILITARY DEVELOPMENT LINES IN TRANSPORT AIRCRAFT

1.1. Technology Gap in Military Transport Aircraft

The C-130 HERCULES and the C-160 TRANSALL account for the bulk of the tactical and logistic transport aircraft employed by the air forces of the European NATO partners. Developed at the end of the fifties or the beginning of the sixties, these aircraft will come to the end of their service life within the foreseeable future and increasingly cause operational and maintenance problems on account of their outdated technologies. Measures to extend their service life should facilitate the employment of these aircraft roughly up to the year 2000.

During that same time frame, the world of civilian transports experienced the successive development and continual production of three generation of aircraft.

Figure 1 shows the "technology gap" in tactical transport aircraft.

Fig. 1. Comparison of Civilian and Military Aircraft Developments. Key: 1—Technology gap; 2—Tactical transport aircraft; 3—Strategic transport aircraft; 4—Technology transfer; 5—Transport aircraft.

1.2. Milestones in Cockpit Evolution, Using the Example of the AIRBUS Aircraft

The avionics equipment of the first European wide-body aircraft, the AIRBUS A300, is based on instruments with analog signal processing exactly as in the case of all other aircraft produced during the early seventies. The aircraft systems are operated by means of directly dedicated switches and buttons. System data are displayed to the crew on a plurality of electromechanical instruments. It takes a three-man crew consisting of captain, copilot and flight engineer to operate the aircraft. Figure 2 shows a cockpit equipped in this fashion.

The general introduction of digital avionics instruments and the use of computer-controlled systems in the second aircraft generation such as:

- Flight Management System (FMS)

- Electronic Flight Instrument System (EFIS)

- Electronic Centralized Aircraft Monitor (ECAM)

leads to a higher degree of automation. The cockpit crew can be reduced to two pilots. The AIRBUS A300 (Fig. 3) is a typical example of this aircraft generation.

Flight control and navigation data are displayed on multifunctional display screens just as are the system data as such, while the power plant parameters are still displayed on conventional instruments. The mechanical switches on the overhead panel are replaced by integrated push buttons ("lights-out" philosophy).

AIRBUS introduced the third generation with the "fly-by-wire" technology of the A320. The conventional control columns are replaced by side sticks that permit unrestricted visibility of the main instrument panel on which the Primary Flight Displays (PFD's) and the Navigation Displays (ND's) are arranged side by side. The power plants are controlled electronically by the FADEC's (Full Authority Digital Engine Controllers). The power plant parameters are also displayed on CRT's (Engine/Warning Display). Only the standby instrumentation still consists of conventional displays (Fig. 4).

1.3. "Dual Use" of Proven "Civilian Technologies"

German Airbus is doing work on designing a new military transport aircraft (FLA—Future Large Aircraft) in cooperation with the other European aircraft producers. In view of the described technology gap, consideration of tried-and-proven "civilian technologies"—in terms of "dual use"—looks highly promising in the light of the high financial expenditures connected with aircraft development, on the one hand, and due to the tight time frame for the required project phases all the way to actual commissioning, on the other hand. Here are areas for a possible technology transfer in the avionics sector:

- Flight navigation/flight control,

- Flight management,

- Display screens (displays),

- Central aircraft monitoring,

- Modular avionics architectures.

2. REQUIREMENTS FOR A NEW MILITARY TRANSPORT AIRCRAFT

Specific military transport missions demand aircraft capabilities going beyond civilian uses. These requirements represent the dimensioning factors both for the overall design and for mission outfitting. Here are some of these requirements concerning cockpit and avionics design:

- Low-level flight (terrain-following flight, terrain/threat avoidance),

- Operation at night and during poor visibility conditions,

- Autonomous on-board precision navigation and landing,

- On-board mission planning,

- Dropping cargo and airborne troops,

- Communication with ground and airborne command posts and operations centers.

These operational requirements, some of which are new for transport aircraft and therefore represent a technological challenge, must be met via engineering solution concepts.

Demonstrating the practical usability of new technologies and analyzing the concept will require the employment of suitable development tools, especially to investigate the complex aspects of man-machine interface (MMI) and of cockpit tasks.

3. DEVELOPMENT TOOLS TO SUPPORT COCKPIT DESIGN

The feasibility and preliminary development phase of a product, such as a transport aircraft, is of great significance because that is the phase when all performance and configuration properties are defined; these properties influence about 85% of the life cycle costs although less than 10% of the life cycle costs are actually spent (Fig. 5).

"Cockpit" here is synonymous with manifold requirements that spring from the various specialized disciplines and contain their specific approaches, such as aerodynamics, structural design, load mechanics, system design, ergonomy, industrial design, etc.

There are many different development aids that are suitable for supporting the various specialized disciplines. The assortment extends from CAD (Computer-aided design) systems via engineering mockups all the way to flight simulators. Their use always represents a compromise between the type or depth of the investigation and the required or, more precisely, the justifiable expenditure. Here are the essential technical goals of the preliminary development phase:

- checking operational requirements;

- demonstration of concept's feasibility;

- analysis of applicable technologies;

-identification of development risks regarding technology availability (Technology Readiness—TR);

- assessment of user acceptance.

The "virtual cockpit" was designed as a developmental tool in the "Cockpit and Avionics Preliminary Development" Division of German Airbus; this tool is used to support cockpit design activities.

4. "VIRTUAL COCKPIT"

The basic idea behind the "virtual cockpit" is the use of SOFTWARE instead of HARDWARE.

It includes the use of modern input and output techniques of latest-generation computers instead of expensive mechanisms and instruments on a mechanical or electrical basis. Long before the ultimate outfitting is available, the "virtual cockpit" represents a comfortable aid which can be used to investigate and analyze questions of man-machine interface in the cockpit.

4.1. Components

The virtual cockpit consists of the following components:

1. User surface, 2. Simulation computer, 3. Operator terminal.

1. The display and output unit is an arrangement of graphic display screens. The arrangement of the display screens is variable. The individual operating elements—such as switches, levers, etc., but also entire panels—can be illustrated to scale on the monitors (Fig. 6). The display screens are equipped with touch-sensitive foils (touch screen) so that interactive switching processes can be carried out with the simulated switches.

The geometric arrangement and size of the simulated display and operating elements on the monitors correspond to the original. The input and output instruments are in a cabin to facilitate undisturbed studies. The general construction is flexible as regards modifications and expansions of the experimental setup (Fig. 7).

2. Several work stations are interconnected by means of Ethernet and TCP/IP (Fig. 8). They energize monitors and touch screens and they also supply warning sounds and synthetic language. The simulation models of various aircraft systems, such as power plants, hydraulics, electrical parts, air conditioning system, etc., run in the computers. The "systems" can be operated in a manner close to real life. The required calculation output is distributed over several RISC work stations; each processor has a specific task. By virtue of the number of work stations employed, the overall calculation output can be adapted to practical utilization requirements. Currently, only computers featuring a certain architecture are in use. But the use of diverse industry standards makes it possible to couple heterogeneous hardware platforms together.

3. Operator Terminal. The operator terminal is used to control simulation. Here, the user has a graphic surface available with whose help he can trigger, among other things, also system errors via the mouse click.

4.2. PRACTICAL APPLICATIONS

The "virtual cockpit" is a flexible tool with many different uses for the purpose of investigating various aspects of cockpit design, such as

- Development of display formats,

- Design of operating panel layouts,

- Development and testing of monitoring algorithms,

- Dynamic simulation of man-machine interactions,

-Investigation of operability of aircraft systems (which and how many switches do I need?),

- Initial analysis of pilot work load,

- Development of abnormal and emergency procedures including alarms, switching actions, and the use of electronic check lists,

- Supply of color printouts of display screens and operating panel to build up cockpit mockups.

4.3. Current Tasks

To simplify the pilots' tasks, the on-board systems of modern passenger aircraft (as in the Airbus A340) are monitored by electronic systems, such as the ECAM (AIRBUS) or EICAS (BOEING). The monitoring algorithms of the monitoring systems are based on error analyses and error propagation models of the system architecture that is specific for the particular aircraft type. The monitoring system and its software therefore are especially tailored for the particular aircraft type.

In the development process, the data required here are available only relatively late because the structure of the systems must first of all be spelled out in detail. This is why particularly good development aids are required to define the monitoring system so as to avoid any subsequent delays, for example, in getting the aircraft licensed.

The "virtual cockpit" is used as rapid prototyping means already during the preliminary developmental phase of the 100-seat regional aircraft project, the RL 92/122 (the old MPC 75) of German Airbus; it is employed in this fashion not only to investigate the requirements for the monitoring system as such but also to look into its interfaces with the connected systems and the information display for the cockpit crew.

This manner of practical application contains all functions of operating and monitoring the aircraft ground systems (Fig. 9). All of the principal systems of the aircraft—such as engines, APU, hydraulics and electric power supply, fuel, and air conditioning system, are simulated dynamically and in real time. They are operated via the overhead panel.

Here are the simulated components of the monitoring system:

- Error identification and diagnosis system with warning logics, flight phase calculation, and warning process logics.

- Operating personnel

- Attention getter main alarm lamps (master lights), acoustic warnings.

- Display system with display management logic, power plant and warning display screen, system and status display screen.

4.4. INVESTIGATION AREAS

Central System Operation:

A logical explanation of the "need-to-know" principle of the present-day aircraft generation (AIRBUS A320) is a "need-to-control" principle and leads to central system operation in the aircraft (see lecture by T. Liebig: "Central System Operation Using Touch Screen"). The required investigations are being performed with the virtual cockpit.

Operation of the Flight Management/Missions Management System (MMS):

A military mission management system (for a transport aircraft) can be construed as an "add-on" to a civilian flight management system.

For this purpose, the MMS communicates with the specific-military mission outfitting, on the one hand, and serves as an interface with the "civilian part" of the avionics, on the other hand, as illustrated in Fig. 10.

Current concept evaluation is concentrated on the following main criteria:

- Operating logic,

- Ergonomy,

- Physical properties,

- Pilot-task coordination.

1. Control Logic

The analysis of the control logic is performed on a stand-alone basis. To do that, simulation of the systems involved is performed regarding their responses to operator inputs, messages, recommendations, and warnings in the case of malfunctions.

2. Ergonomic Aspects

The assessment of the ergonomic aspects such as the selection of the place where the touch screens and the arm rests are to be installed, the formats of graphic information output, and the visual feedback can also be accomplished on a stand-alone basis. Some investigation points, however, required a somewhat more comprehensive cockpit environment. For instance, it is necessary to consider the noise spectrum inside the cockpit when investigating the acoustic feedback.

Other investigations, such as, for example, concerning the touch field size, the pressure thresholds, the mechanism of function initiation require a motion system and thus a full flight simulator.

3. Physical Properties

The investigations of the physical properties of the operating units, such as display screen resolution, touch surface resolution, and the available touch-sensitive technologies can also be performed on a stand-alone basis.

4. Pilot-Task Coordination

The influence of simultaneous and competing pilot tasks, such as ATC communication, navigation, is investigated after successful investigation of the analysis criteria described. An operational flight simulator environment is required for these investigations.

The following table (Table 1) points up the possibilities of the "virtual cockpit" and its suitability for the development and analysis of a new concept.

Table 1. Areas of Use for "Virtual Cockpits"

Investigative aspect;	Investigative environment		
	"Virtual Cockpit"		Flight simulator
	Stand-Alone Mockup	System Simulation	
Monitoring Logic			
System levels	x	x	
Information structure	x	x	
Operating possibilities (Options)	x	x	
Procedure	x	x	
Priorities	x	x	
Functions (skip, clear, cancel, etc.)	x	x	
Ergonomic Aspects			
Installation site	x		
Arm rest	x		
Size of operating panel			(Motion)
Acoustic feedback			(Noises)
Visual feedback	x		
Touch pressure	x		(Motion)
Function initialization (touch and lift)	x		(Motion)
Graphic output (shapes, colors, captions, etc.)	x		
Physical Aspects			
Display screen resolution	x		
Touch screen resolution	x		
Simultaneous touch inputs	x		
Available touch overlay technologies	x		
Dimensions	x		
System output	x		
Coordination of Pilot Tasks			x

5. SUMMARY

Work to define a follow-on aircraft for the C-160 or C-130 has been started by German Airbus. It seems possible to compensate the technology gap—caused by the absence of corresponding projects of tactical transport aircraft over the past 30 years—through the transfer of suitable "civilian" technology. High mission requirements, tight budgets, and a narrow time frame call for the use of modern development aids.

The "virtual cockpit" was built by German Airbus as a design and investigation tool for cockpit design. Here were the pilot applications:

-Concept of system monitoring for the 100-seat RL92/122;

-Design and demonstration of a concept for a central display and operating unit for aircraft systems. This

work was done in the context of the FANSTIC Project of the German BRITE/EURAM Research Program.

Plans call for using the "virtual cockpit" also for designing the FLA cockpit. Training cockpit and maintenance personnel with respect to on-board systems and their monitoring functions is another area of possible use.

Germany: Technology Development During Manned Space Flight

Using Finite Element Method to Calculate Energy Rates Upon Delamination of Carbon Fiber-Reinforced Plastics

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[Article by R. Krueger, ISD, University of Stuttgart and Th. Schneider, Dornier Luftfahrt GmbH, Friedrichshafen: "Calculation of Energy Release Rates in Delamination of Carbon-Fiber-Reinforced Plastics Using the Finite Element Method"]

[Text]

1. Overview

One of the main forms of damage in fiber-reinforced plastics is delamination, that is to say, the thin-sheet separation of two neighboring laminate layers. Due to operational stress, a delamination caused by manufacturing flaws or impact is enlarged, at first rather gradually, and then with increasing speed. The resultant decline in the stiffness and strength of the component can lead to the failure of the structures already below the stress limit for which the component was designed. Design and layout of complex components consisting of fiber-reinforced plastics with the help of empirically determined safety factors can, of course, prevent the structure's delamination failure; but this is no way to make optimum use of the structures; instead, they will have excessively large dimensions and this, in turn, will lead to an undesirable, heavy weight. To make optimum use of the favorable properties of fiber-reinforced plastics and to determine inspection intervals, it is necessary to be able to predict the propagation of delaminations.

In the following investigations, it is assumed that the linear-elastic fracture mechanics for carbon-fiber-reinforced plastics can indeed be used, although nonlinearities are considered on account of big shifts (geometric nonlinearities). It is furthermore assumed that there is no critical energy release rate G_c and that this is a property of the material that is independent of the geometry and the layer buildup. Delamination can thus begin to progress when the energy release rate G that is available due to the outer loads and the stored expansion energy reaches the critical value G_c. To be able to predict the delaminations in a carbon-fiber-reinforced plastic component, one needs numerical procedures along with a knowledge of the critical energy release rates of the particular raw material for the three types of crack opening and their superposition; using these numerical procedures, one can calculate the available energy release rates G_I, G_{II}, and G_{III} for a complex component under the given load. Various processes are available in this connection and they are based on the method of finite elements.

2. Preliminary Experimental Work

Several simple samples were developed for the experimental determination of the critical energy release rates G_c. The DCB (Double Cantilever Beam) sample is used for the determination of G_{Ic}; the ENF (End Notch Flexure) sample is used to determine G_{IIc} (DIN [German Industrial Standard] 65563). The DCB and ENF samples with unidirectional and quasi-isotropic layer buildup from T300/1076 were made at Dornier and the critical energy release rates under quasistatic load were determined experimentally in the works of Koser (1) (see Fig. 1) and Buergmann (2) with the help of various analysis methods that are based on different theories and assumptions.

To be able to get data on the interaction of the three types of crack openings, one must investigation the behavior of more expensive samples, such as those that were described, for example, by Buergmann et al. (3). In this case, a simple analytical or empirical analysis of the experimental data is no longer possible. Other methods, which, for example, are based on the method of finite elements must be employed here. This first of all requires detailed test calculations with the above-described simple DCB and ENF samples to test the reliability of the calculation methods.

3. Numerical Methods to Calculate Energy Release Rate

The virtual crack extension method and the modified crack closure method were selected for testing from among the various methods used to calculate the energy release rate; a single finite-element analysis suffices to determine the energy release rate when these two methods are employed.

Looking at a structure discretely constituted with finite elements, then we label the vector of the junction point shifts with $\mathbf{r}$ and the vector of the corresponding loads with $\mathbf{R}$. The work dW, which is done by the external forces in case of an infinitesimal crack area enlargement of dA, then looks like this:

where $W = \mathbf{R}^t \times \mathbf{r}$; $dW/dA = d\mathbf{R}^t/dA \times \mathbf{r} + \mathbf{R}^t \times d\mathbf{r}/dA$

and the change in the expansion energy U stored in the supporting structure is:

where $U = \frac{1}{2} \times \mathbf{R}^t \times \mathbf{r}$; $dU/dA = \frac{1}{2} \times (d\mathbf{R}^t/dA \times \mathbf{r} + \mathbf{R}^t \times d\mathbf{r}/dA)$.

Let us now look at the case where **R** is constant; that would be the load-controlled experiment; if we do this, then we get:

$dW/dA = \mathbf{R}^t \times d\mathbf{r}/dA$ and $dU/dA = \frac{1}{2} \times \mathbf{R}^t \times d\mathbf{r}/dA$.

For the energy release rate G, we then get:

$G = dW/dA - dU/dA = \frac{1}{2} \times \mathbf{R}^t \times d\mathbf{r}/dA$.

Let us now look at the case where **r** is constant; that would be the travel-controlled experiment. The following applies during the advance of the crack:

$W = 0$ yields $dW/dA = 0$ and $dU/dA = \frac{1}{2} \times d\mathbf{R}^t/dA \times \mathbf{r}$.

We then get the following for the energy release rate:

$G = dW/dA - dU/dA = -1/2 \times d\mathbf{R}^t/dA \times \mathbf{r}$.

In a discretized structure, one can also prescribe mixed marginal conditions; that would correspond to a combination of the above-described cases. In the specific case, this means that the external loads **R** are prescribed at a certain number of junctions, while the **r** shifts are set freely until equilibrium has been established. These junction points have so-called local degrees of freedom. The **r** shifts are prescribed at other points and **R** is the vector of the reaction forces that are necessary to establish equilibrium.

If we now split up the load vector and the shift vector into local (Index L) and prescribed (Index P) degrees of freedom, we get the following:

$G = \frac{1}{2} \times \mathbf{R}^t_L \times d\mathbf{r}L/dA - \frac{1}{2} \times d\mathbf{R}^t_P/dA \times \mathbf{r}P$.

3.1. Virtual Crack Extension Method

If we start with the above-derived relationship:

$G = \frac{1}{2} \times \mathbf{R}^t_L \times d\mathbf{r}L/dA - \frac{1}{2} \times d\mathbf{R}^t_P/dA \times \mathbf{r}P$

in which $\mathbf{R}_L$ and $\mathbf{r}_P$ are fixed marginal conditions, then one gets the following with the help of the relationships:

$= \mathbf{a} \times \mathbf{r}$ and $\mathbf{R} = \mathbf{a}^t \times \mathbf{P}$

here, is used to label the vector of the element shifts, **P** designates the vector of the element forces, and **a** marks the matrix of incidence:

$G = \frac{1}{2} \Sigma (\mathbf{P}^t \times d/dA - d\mathbf{P}^t/dA \times)$.

In this relationship, one must add up via all elements in the structure. If one now replaces $\mathbf{P}^t$ with:

$\times = \mathbf{P}$ yields $\mathbf{P}^t = {}^t \times$,

where designates the symmetrical element stiffness matrix—then one gets the following by way of an intermediate result:

$G = \frac{1}{2} \Sigma ({}^t \times \times d/dA - d({}^t \times)/dA \times)$

$G = \frac{1}{2} \Sigma ({}^t \times \times d/dA - d^t/dA \times \times - {}^t \times d/dA \times$
).

The first two terms in the parenthesis cancel each other out. We thus get the following for the calculation of the energy release rate"

$G = -1/2 \Sigma ({}^t \times d/dA \times)$.

In this equation, d is the change in the element stiffness matrix due to a virtual crack extension δa that leads to an increase in the crack surface dA.

The basic procedure involved in the virtual crack extension method (4, 5) is illustrated in Fig. 2 for the two-dimensional case. The crack is expanded virtually by δa along the visualized crack path by means of a simple shift in the junction point at the tip of the crack (due to the change in the junction point coordinates). The method calls for only one single complete finite-element analysis of the overall structure, the calculation of the element stiffness change due to junction point shifting, and the analysis of the results according to the above relationship. Here, we add up only via the elements that are directly connected with the tip of the crack; all other elements are not influenced by the change in coordinates. The "differential" change in the stiffness matrix d was determined in the study at hand by subtraction of the original stiffness matrix from the one that was calculated after a "virtual" crack extension by δa (5, 6, 7). It is however also possible to calculate d/dA analytically. To do that, however, one must make up an additional element program for each element type (8).

The procedure for the three-dimensional case is basically the same. Once the process has been implemented into the program, it can be taken over unchanged. There are several ways to handle the junction point shift. To begin with, all junctions can be shifted by δa along the crack front. In that way, one gets the entire energy release rate in analogy to the two-dimensional case. In general, however, one will be interested in the local energy release rate along the crack front. In that case, as shown in Fig. 3, one will proceed junction by junction and thus work one's way along the crack front, step by step. The choice of the junctions to be shifted will be determined by the crack surface enlargement dA. In doing this, the corner junctions are each time shifted by δa and the middle junctions of the adjoining elements are each time shifted by $\frac{1}{2}\,\delta a$. In that way, one forces a linear crack surface enlargement in elements with quadratic shifting setup and one avoids the parabolic crack surface boundaries described in (7). The energy release rate which one determines in each case over two element lengths is then matched up with the corner junction that has been shifted by δa. Reliable values were determined for the energy release rates for virtual crack extensions of δa in the range of 10^{-3} to 10^{-5} times the element length. Smaller virtual crack extension are basically possible, but one must observe the length of the computer word, because almost identically large stiffness values are subtracted to determine d. Under unfavorable circumstances, the differences in the stiffnesses can be so small that they will no longer be numerically recordable and that leads to nonsensical results.

The crack extension method described above and used exclusively in this study permits only a calculation of the total energy release rate G. It is therefore impossible to determine the contribution of G_I, G_{II}, and G_{III} to G, unless the analytical interrelationships are known a priori. Expanded methods for the calculation of G_I, G_{II}, and G_{III} were proposed in (9, 10), but they were not investigated in this study here.

3.2. Modified Crack Closure Method

The crack closure method is based on the fact that the energy ΔE that is released when a crack is extended from a to $a + \Delta a$ is equal to the work that is necessary to close the crack between $a + \Delta a$ and a. Looking at the discretized, two-dimensional structure which is idealized with eight-junction quadratic elements, we can easily determine the work that is necessary to close a crack having the length of one element side (Fig. 4).

ΔE = 1/2[X_1 x Δu_1 + X_2 x Δu_2) + (Y_1 x Δ[<i]talv$_1$ + Y_2 x Δ[<i]talv$_2$)].

Here, X_1 and X_2 as well as Y_1 and Y_2 signify the forces at the junction points that must be closed; Δu_1, Δu_2, Δv_1, Δv_2 are the shifts at these junctions as shown in Fig. 4. The restoration of the original state prior to the advance of the crack is the result of the junctions being pulled together. This is why the forces needed for closure are identical to those that are at work between the top and the underside of the closed crack. These cutting forces X_i and Y_i can be determined by way of a finite-element analysis if the crack is still (once again) closed; the shifts Δu_i and Δv_i can be determined in a second finite-element calculation where the crack is opened along length $a + \Delta a$. In this method, that is, the crack closure method, the real forces and the real shifts are used to calculate the work ΔE. The energy release rate value thus obtained is associated with the crack length $a + \delta a/2$ (11, 12).

The modified crack closure method is based on the same considerations as the above-mentioned direct method. But here it is assumed that—in case of a crack advance from $a + \Delta a$ to $a + 2\Delta a$ (Fig. 4)—the shifts behind the new crack front at $a + 2\Delta a$ are approximately equal to the shifts behind the original crack front at $a + \Delta a$ (Δu_i, Δv_i in Fig. 4) (13). The energy available for crack advance from $a + 2\Delta a$ to $a + \Delta a$ corresponds to the energy necessary to close the crack from $a + 2\Delta a$ to $a + \Delta a$. It can be calculated for the eight-junction element according to:

$\Delta E = 1/2[(X_{1'} \text{ x } \Delta u_1 + X_{2'} \text{ x } \Delta u_2) + (Y_{1'} \text{ x } \Delta v_1 + Y_{2'} \text{ x } \Delta v_2)]$

—using the forces $X_{1'}$, $X_{2'}$ and $Y_{1'}$, $Y_{2'}$ ahead of the crack front (length $a + \Delta a$) and the shifts Δu_1, Δu_2, Δv_1, Δv_2 along the junctions behind the crack front. The energy release rate value thus obtained is associated with the crack length $a + \Delta a$ (11, 12). Only a finite-element analysis is required to calculate the energy release rate according to this method. The total energy release rate G can be written as follows:

$G = G_I + G_{II} + G_{III}$

where the G_I indicate the energy release rates for various crack opening types. We get the following for the two-dimensional case where

$G_I = 1/\Delta a \text{ x } b \text{ x } 1/2(Y_{1'} \text{ x } \Delta v_1 + Y_{2'} \text{ x } \Delta v_2)$

$G_{II} = 1/\Delta a \text{ x } b \text{ x } 1/2(X_{1'} \text{ x } \Delta u_1 + X_{2'} \text{ x } \Delta u_2)$

where b designates the sample width. Using the modified crack closure method, one must keep in mind that all elements around the tip of the crack are of the same type (kinetically compatible) so as not to cause any overlaps. For the same reason, the crack must always be opened (closed) by elements and this is something one must watch out for when dealing with elements of a higher order (11, 12, 14).

The great advantage deriving from the crack closure methods consists of the direct splitting of the energy release rate into the portions G_I, G_{II}, and G_{III}. The results of the original and the modified crack closure method are almost identical for sufficiently fine grids in the surroundings of the crack tip; however, in the case of the modified crack closure method, one needs only a single complete finite-element analysis; that makes for big computer time savings when coping with big problems featuring many degrees of freedom and above all in case of nonlinear calculations.

Figures 5 and 6 will now help explain the use of the method in dealing with three-dimensional problems. As in the case of the virtual crack extension method discussed earlier, there are several possibilities here for successively working along the crack front and thus determining the local energy release rate along the crack front. To keep the formulas for G_I, G_{II}, and G_{III} as simple as possible, it will be assumed that the elements along the crack front have almost identical side lengths. The crack is closed in an imaginary (virtual) fashion over the surface [dD]A that is shown hachured. One gets the following as a result of the shifts Δu_i, Δv_i, Δw_i at the junctions i = 1.4 and the forces X_j, Y_h, Z_j at the junctions j = 1', 4':

$G_I = 1/21/\Delta A(1/2Y_1\Delta v_1 + Y_2\Delta v_2 + 1/2Y_3\Delta v_3 + Y_4\Delta v_4)$

$G_{II} = 1/21/\Delta A(1/2X_1\Delta u_1 + X_2\Delta u_2 + 1/2X_3\Delta u_3 + X_4\Delta u_4)$

$G_{III} = 1/21/\Delta A(1/2Z_1\Delta w_1 + Z_2\Delta w_2 + 1/2Z_3\Delta w_3 + Z_4\Delta w_4)$.

The energy release rate determined over the area ΔA is matched up with junction 2' on the crack front. The factors ½ —where the first and third summands having the above formulas are necessary because only half the forces need be considered along the left and right edge of surface ΔA. The other half of the force components is considered in the calculation of the energy release rate of the neighboring area. Other possibilities of closing the crack along the crack front mentally are described in (15, 16, 17). But one must always make sure that the crack surface will be closed in a kinetically compatible fashion. Furthermore, the sum of all crack closure work G_{I_j} x ΔA, G_{II_j} x ΔA and G_{III_j} x ΔA along the j supporting junctions

must always be equal to the total crack closure work $G_I \times \Delta A_{total}$, $G_{II} \times \Delta A_{total}$ and $G_{III} \times \Delta A_{total}$ that one gets by a one-time crack closure along the entire crack front.

4. Calculation of Energy Release Rates and Comparison to Experimental Results

Two-dimensional and three-dimensional finite-element calculations were performed on DCB and ENF samples. The behavior of the numerical procedures and their accuracy was checked out because the particular crack opening type is known for the samples and because there are various analysis formulas to calculate the energy release rate. In complex samples or real components for which there are no analytical calculation formulas, one must depend on the reliability of numerical methods such as those tested here.

4.1. Results of Two-Dimensional Finite-Element Analyses

The first investigations were conducted on two-dimensional models of the DCB and ENF sample. The NOVA finite-element program developed by the ISD [Institute for Statics and Dynamics of Aviation and Space Flight Construction] was used for all finite-element calculations (18). The load or deformation values that were determined experimentally and that were necessary as input data for finite-element analysis come from the work of Koser and Buergmann (1, 2). In his work, Koser investigated eight 250-mm long, 25-mm wide DCB samples with crack lengths of between 31 and 112 mm from 24 unidirectional layers of Prepreg T300/1076. Buergmann determined the energy release rates on 12 ENF samples with a length of 150 mm and crack lengths between 20 and 35 mm; the width and layer structure were identical to those of the DCB samples. The load P that led to delamination growth at a crack length of a is given in (1, 2); the determined energy release rates can thus be considered to be critical G values.

With the help of symmetry considerations, one can get by with modeling only half of the DCB sample. The samples were modeled with eight-junction rectangular elements. Half the sample thickness was discretized with three element layers each. The sample was subdivided into several sectors in terms of length. The sector in the immediate vicinity of the crack tip (3 mm ahead of and 3 mm behind the crack tip) was subdivided into 4 to 96 elements for convergence investigations and the structure outside the crack sector was subdivided into 40 to 50 elements.

Figures 7 and 8 illustrate the results of the finite-element analyses and the experimental evaluation for one DCB and ENF sample each. Here one can clearly recognize the scatter of the various experimental analysis methods. Both finite-element methods—virtual crack extension method and modified crack closure method—provide good agreement when compared to each other, and agreement is satisfactory when compared to the experimental values. The values for the ENF sample were too low; they were due to a somewhat too high degree of stiffness in numerical simulation that also emerged upon contemplation of the maximum elastic deflection at the load attack point.

4.2. Three-Dimensional Finite-Element Analysis of a DCB Sample with Straight and Curved Crack Front

Three-dimensional analyses make it possible to determine the local course of the energy release rate along the crack front; however, a two-dimensional finite-element calculation can supply only a value that is averaged over the width of the sample. That might suffice for simple samples; but for complicated samples (3) or real components, one will as a rule need a three-dimensional analysis. In addition to checking the methods for reliability and making a comparison with values derived from the two-dimensional analysis and from experiments, it was interesting—in the case of the DCB sample—to learn whether the methods facilitate and statements about the course of the crack front inside the sample. Starting with a linear crack front—formed by the separating foil—experiments with advancing crack length revealed increasingly curved crack fronts which however became visible only after the end of the experiments when the samples were broken open (1, 2). Figure 1 shows traced crack fronts of a sample that was broken open.

The subdivision shown in Figs. 9 and 10 was chosen for the sample's finite-element modeling. For reasons of symmetry, only one quarter of the sample was idealized here with 20-junction full-body elements. As in the two-dimensional case, this presupposes that the crack continues to run along the plane of crack initiation and that the symmetry is thus preserved. This assumption can be justified in the light of the experimental results for unidirectional layer structures in spite of some fiber bridges. The grid buildup essentially corresponds to a two-dimensional grid expanded into the third dimension as shown in Fig. 9. To be able to investigate crack lengths of $a = 50$ mm and $a = 111.5$ mm, only 150 mm of the total sample length of 250 mm were modeled. Test calculations showed that the sample part neglected here does not influence the results because the tensions and elastic expansions in front of the crack fade to zero rather rapidly. Convergence investigations furthermore showed that subdividing the crack sector into 16 elements makes for good accuracy (Fig. 10). At first, five elements were used over the sample width. The edge sector of the sample was refined later to be able to determine the course of the energy release rate more accurately there. Models of half the sample were also investigated for comparison purposes and for later use with the ENF sample. Fig. 11 which comes from the analysis of a half-model shows the deformation behavior of the sample with a crack length of $a = 111.5$ mm. In Fig. 12, the curve of the energy release rate is plotted against the sample width for the sample having a crack length of $a = 111.5$ mm with an experimental load of $F = 12.66$ N. For comparison, the scatter range of values determined from the experiment and the results deriving from the two-dimensional analysis were plotted for the two calculation methods that were used. The three-dimensional results show an almost constant curve of the energy release rate in the middle of the sample over [illegible] of the sample width. The energy release rate decreases gradually and then increasingly toward the

edge. Both methods reproduce the curve in a qualitatively equal fashion. In the middle of the sample, the results of three-dimensional analysis are somewhat above those deriving from the two-dimensional analysis, whereas along the edge they are definitely below. The result of two-dimensional analysis corresponds to a value that was averaged over the sample thickness as was to be expected.

If one looks at the curve of the energy release rate over the width of the sample from the viewpoint of crack advance, then one can assume that the straight crack front—that reveals a higher available energy release rate in the center of the sample—reaches the critical value there first. Consequently, the crack will first begin to grow in the middle of the sample whereas crack growth toward the edge will start later due to the smaller available energy release rate. Accordingly, the crack will race forward in the middle and will thus progressively form a curved crack front. This assumption supplies an explanation for the fact that the crack fronts are curved toward the edge as happened in the experiment (Fig. 1) (19, 16).

The finite-element model illustrated in Figs. 13 and 14 was used to describe the curved crack fronts. A crack length of a = 111.5 mm was chosen along the edge for the modeled sample; this corresponds to the length measured in the experiment along the free edge which was also assumed for two-dimensional and three-dimensional analysis with linear crack front. A G-curve—that led to an almost constant energy release rate over the sample width all the way to the vicinity of the edge (Fig. 12)—was determined over the sample width for this particular curved crack front. If one now compares the curve of the energy release rate at the assumed curve crack front to the one of the linear crack front, then one may assume that there is a crack front for which the energy release rate $G(s)$ along the crack front s is constant, all the way to the edge of the sample $G(s) = G_I = const$. $G = G_I$ follows from the symmetry of the sample geometry and the load applied with respect to the plane of the crack's course. That also applies to the curved crack front, that is to say, $G_{II} = G_{III} = 0$ along the entire crack front. Considering the above-mentioned experimental scatter of the crack fronts, one can furthermore postulate that the described crack front $G(s) = G_I = const$ is formed from the linear crack front and that the latter grows uniformly the moment $G(s)$ reaches the critical value of $G(s) = G_{Ic}$. To confirm this assumption, one would have to perform a statistically relevant number of experiments and the average crack front curve would have to be determined. A finite-element analysis with this crack front curve would then show whether the assumption $G(s) = G_I = const$ is then met up to the very edge of the sample.

4.3. Three-Dimensional Finite-Element Analysis of an ENF Sample

Half a sample was idealized for the three-dimensional model of the ENF sample; here, the element distribution was the same as in the case of the above-described DCB sample. The full sample length of 150 mm was considered in each case. Figure 15 shows the deformed ENF sample with a crack length of a = 30 mm at an experimental load of F = 503 N.

The curve of the energy release rate is plotted against the sample width in Fig. 16 as in the preceding chapter. For comparison, the scatter range of the values determined from the experiment and the results of the two-dimensional analysis for both calculation methods are also plotted here. One can recognize an energy release rate curve that is nearly constant over the entire sample width for a crack front assumed to be linear. The values from two-dimensional and three-dimensional analysis agree very nicely. The results permit the conclusion that the crack front will remain almost linear and that it will advance uniformly because G_{IIc} is attained uniformly along the predetermined initial crack front. This is confirmed by the crack fronts observed in the ENF samples that were broken open (2).

5. Summary

This study investigated various numerical methods for the calculation of energy release rates that are based on the method of finite elements, initially rather in detail on two-dimensional models of DCB and ENF samples. The results determined from finite-element analysis were compared to those energy release rates that were determined with the help of standardized analysis formulas derived from the experimental data. Compared to the virtual crack extension method such as it was applied here, the modified crack closure method offers the advantage that one can split up the total energy release rate G into the positions G_I, G_{II}, and G_{III} that belong to the crack opening types. Comparison to the experimentally determined energy release rates yielded good agreement.

By testing the numerical methods on the DCB and ENF samples, it was possible to check their reliability so that calculations of samples and components are now possible for which no analytical solutions are available. Furthermore, it was possible to determine the curve of the local energy release rates along the delamination front with DCB and ENF samples. An almost constant G_I was determined for a linear crack front in the case of the DCB sample only in the middle of the sample in a sector extending over about 60% of the sample width; G_I drops definitely toward the edge of the sample. An approximately constant curve of G_I over the entire sample width was calculated along an assumed curved crack front. An approximately constant curve of G_{II} over the sample width resulted for the linear crack front in the case of the ENF sample. The following conclusions were thus arrived at:

- In the DCB sample assuming a linear initial crack front, a crack growth will set in first of all in the sample center due to the G_I curve along this crack front and a new crack front curved toward the edge

will be the consequence. This was confirmed experimentally.

- For the DCB sample, there is presumably a curved crack front along which the energy release rate G_I is constant over the entire sample width. This emerges clearly as a result of the finite-element analyses on samples with linear and curved crack fronts.
- It is thus postulated that in the case of the DCB sample a linear initial crack front in response to loading can change into a curved crack front with $G(s) = G_I = G_{Ic}$ which will then run uniformly through the sample. Confirmation necessitates more comparisons between experiments and numerical simulation.
- In the case of the ENF sample due to the almost constant G_{II} along a linear crack front, the latter will remain linear and will run almost uniformly through the sample. This was confirmed experimentally.

Additional experimental and numerical investigations on the curved crack fronts of the DCB sample and more complex samples (3) are required in order correctly to interpret the physical interrelationships.

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Germany: Technology Development During Manned Space Flight

Positioning Force, Power Absorption in Electromagnetically Suspended Device TEMPUS

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[Article by S. Sauerland, G. Lohoefer, I. Egry: "Positioning Forces and Power Absorption in the TEMPUS Electromagnetic Levitation-Melting System"]

[Text]

Overview

An electromagnetic levitation system is to be used to investigate the thermophysical properties of undercooled molten baths in a state of weightlessness. Smooth experimentation requires stable positioning of the sample and good controllability of the sample temperature. This is an overview of the current state of the theory on the approximate calculation of the levitation force and power absorption in levitated samples; we also present an improved theory. The theories are tested on the basis of measurements performed on a levitation coil designed especially for use under low-gravity conditions.

1. Introduction

Today, electromagnetic levitation technique is a widespread method used for processing liquid metals without the use of containers. One of the method's chief advantages resides in the avoidance of sample contamination due to the use of highly-pure processing gases and no-contact measurement procedures. This facilitates investigations also on highly reactive molten metal baths without adulteration of measurement results due to interference from chemical reactors with the crucible material.

Another great advantage resides in the avoidance of heterogeneous germ formation along crucible walls; that makes the area of metastable undercooled molten baths accessible to in-situ investigation. This permits direct observation of the rigidification process from the molten bath and an investigation of the attendant questions regarding phase selection in balance or development of metastable phases. A knowledge of specifically material-related data of the undercooled molten baths is necessary to understand all of these procedures because practically all relevant processes in the molten bath—such as, for example, convective instabilities, germ formation rates, and rigidification speeds depend on thermophysical properties, such as specific heat capacity, heat conductivity, or viscosity.

In this connection, Dornier developed the electromagnetic levitation system TEMPUS as part of a contract from DARA [German Space Agency]; this system is designed to make it possible to investigate thermophysical properties of undercooled molten metal baths under conditions of weightlessness. An overview of the vast number of experiments to be conducted in this system during the IML-2 Spacelab mission and the COLUMBUS PRECURSOR MISSIONS can be found, among other things, in (1).

This article deals with the problem of calculating the positioning forces and the power absorption in the sample material using the example of the TEMPUS levitation coils that were designed for use under conditions of weightlessness.

2. Theory

2.1. Conventional Linear Theory

When a metallic sample is placed in an external, magnetic alternating field, its eddy currents are induced. This, on the one hand, means that a Lorentz force acts upon the sample due to the reciprocal interaction of the eddy currents with the outer field and, besides, it indicates that the sample is heated up by the ohmic losses of these currents. The theory of Okress (2) and Rony (3) that is usua y employed describe these phenomena starts with the assumption that the external magnetic field varies only slightly in the area of the sample. Then its Taylor development can be broken off after the first member and one gets the known result for the first-order Lorentz force acting on the sample (4):

F = - grad (**m** x **B**),

where **m** refers to the metal sample's magnetic dipole moment that is generated by the eddy currents. If for **m**, one inserts the magnetic dipole moment of a nonferromagnetic, well-conducting sphere in a homogeneous, sinusoidally alternating magnetic field (5), then one gets the following for the temporally-averaged force acting upon the sphere (3):

F-bar = $-\pi R^3/\mu_0$ G(q) grad ^{2}-bar

where:

G(q): = 1 - 3/2q sinh(2q) - sin(2q)/cosh(2q) - cos(2q).

q: = **R**/δ and δ = square root of 2/(ωσμ_0 is the skin penetration depth, and **R** and σ are used to label the radius or the electrical conductivity of the metal sphere.

The temporally-averaged absorbed power of a nonferromagnetic, well-conducting sphere—that is exposed to a homogeneous, sinusoidally alternating magnetic field—now looks like this (3, 5):

P-bar = 6π**R**/σμ^2_0 H(q) **B**^{2}-bar

where:

H(q) = (q sinh(2q) + sin(2q)/cosh(2q) - cos(2q)) - 1.

If one adds the known formulas for the magnetic fields generated by ring currents, then one gets a complete description of the theory of levitation for slightly nonhomogeneous fields.

2.2.1. Problem

The above-mentioned formulas provide a good description only if the diameter of the spherical sample is small when compared to the characteristic dimensions of the coil system. But that is not always guaranteed in practice. Figure 1 shows a scale illustrate of a coil system with sample, such as it is used in the TEMPUS µg levitation system. Here, the ratio between the sample radius and the coil radius is about 1:2.

The TEMPUS levitation coil system consists of two coils, a positioning coil and a heating coil. The heating coil has four windings and generates a dipole field with a frequency of 427 kHz. The positioning coil consists of four windings above and below the heating coil through which current flows in opposite directions. A quadrupole system is thus generated. The working frequency is 144 kHz.

In Figure 2, the appearing magnetic field and the magnetic field gradient are plotted on the coil axis for a typical coil current of $\mathbf{I}_0$ = 100 A for the heating coil.

If one uses formula (2) to calculate the force, then—for a sample in the center of the coil—one finds a vanishing total force because the gradient disappears there and because the forces on the top and underside of the sample just compensate each other on account of the symmetry also when the sample radii are great. Here, one does not expect any errors in the use of the approximation solution because the symmetrical geometry causes the dependence on the radii to disappear. On the other hand, one does expect deviations when the sample is moved out of this central position.

The situation is more difficult when it comes to the calculation of power absorption. Samples with a large diameter "see" definitely differing fields on the top edge and lower edge as well as on the side due to the field gradients; the effects of these differing fields are not canceled out by the symmetry. Using formula (4), inserting the magnetic field in the coil center, cannot lead to a significant error in estimating the absorbed power if one works with nonhomogeneous magnetic fields in the case of extended samples, such as they appear in practice.

One expects similar deviations in the case of the positioning coil. Figure 3 shows the magnetic field and the field gradient on the coil axis for the positioning coil at a coil current of $\mathbf{I}_0$ = 100 A.

In this coil, likewise, a sample in the center of the coil does not experience any total force because the magnetic field disappears here.

When one calculates the power absorption, on the other hand, one encounters the same problem as in the case of the heating coil. Insertion in formula (4) does not supply and power absorption here, for example, in the middle of the coil, because **B** = 0 magnetic field prevails in the coil center. Working with sample dimensions occurring in practice, however, there are always problems in areas of nonvanishing field intensity so that the power absorption in the sample is seriously underestimated in this case.

The question now is as to what extent these approximation formulas are suitable for describing real coil systems or whether an expansion—including correction terms of higher orders—would provide a significant improvement in the calculations in the case at hand.

2.2. Exact Description

The exact description starts with a spherical metal sample in a magnetic alternating field that is generated by several sinusoidally alternating, otherwise random current density distributions. The basic quasistatic Maxwell equations are completely solved by series expansion. Using this solution, one can then calculate the induced eddy currents and the temporally-averaged levitation forces and absorbed powers. Details of this derivation are described in (6) and (7).

One gets the following for the temporally-averaged induced thermal output in the case of concentric circular current loops in-situ ($\mathbf{r}_n$, θ_n) (see Fig. 1), that in each case carry a current $\mathbf{I}_n$ with frequency ω_n and phase α_n:

P-bar$_s$ = $\pi/2R_s\sigma_s$ $\Sigma_{n,n'}$ $\Sigma^{\infty}{}_{i=0}$ Re
$_i(q_n)$
x $\delta_{\omega n,\ \omega n'}$ $\cos(\alpha_n - \alpha_{n'})$ $I_{n,i}$ - $I_{n',i}$

where:

$H_i(q_n)$: = - (1 + i) q_n $J_{i+1/2}((1 + i)q_n)/J_{i-1/2}((1 + i)q_n)$.

Once again, δ_n: = square root of $2/\omega_n\sigma\mu_0$ designates the skin penetration depth and q_n: = R/δ_n. The $J_{i+1/2}$ designate Bessel functions for half-integral indices.

One gets the following analogously for the levitation force acting on the symmetry axis:

F-bar$_z$ = $\mu_0 R_s \pi/2$ $\Sigma_{n,\ n'}$ $\Sigma^{\infty}{}_{i=0}$ $\Sigma_{m=+/-1}$ Re
$_i(q_n)e^{-i(\alpha_n - \alpha_{n'})}$
x a_i + 1,m/a_1,m $I_{n',i+1}$ x $I_{n,i}$

where:

$G_i(q_n)$: = - $J_{i+3/2}((1 + i)q_n)/(2i + 1)J_{i-1/2}((1 + i)q_n)$

as well as:

$a_{i,m}$ = $(-1)^{i+m}$ square root of (4π/2i+1 (i+m)(i-m)!).

The following applies both to the power and to the force:

$I_{n,i}$ = square root of (2i+1/I(I+1) $I_n(R_s/r_n)$ sin θ_n
$P_i{}^1(\cos\theta_n)$)

where P_l^1 refer to the associated Legendre polynomials.

One can recognize that the solutions represent developments toward R_s/r_n, with l here indexing the development.

3. Results

3.1. Levitation Force

Measurements of the levitation force on a copper sample were performed in the TEMPUS heating coil to compare the accuracy of formulas (2) and (8).

Figure 4 shows the experimental setup for measuring the levitation force acting on the sample.

A copper sphere (θ = 10 mm) was suspended on a compensation scale and run into the middle of the heating coil. Then various sample positions were established on the coil axis and the working Lorentz force was determined by varying the coil current. The measurements were made at room temperature (T similar to 20°C). Care was taken to use only short measurement times so as to avoid any heating of the sample and thus any change in the sample material's conductivity. The coil current was determined by calipering the voltage drop V_0 on the condenser (capacity C) of the oscillating circuit via $i_0 = \theta C V_0$.

The acting force is plotted in Fig. 5 as a function of the position on the coil axis for different coil currents. The solid line corresponds to the expanded theory (8) (calculated up to the fifth order); the broken line corresponds to the linear approximation (2).

One can see that the measurement values are closer to the expanded theory than to the approximation solution; the differences however disappear as the sample is positioned in the coil center. That was to be expected according to the line of argument used in Chapter 2.1.1. A comparison of the theories for the positioning coil is plotted in Fig. 6.

The differences are minor as seen earlier in the case of the heating coil. The relative difference amounts to a maximum of about 10%.

3.2. Power Absorption

The power absorption of a copper sphere (θ = 10 mm) was calculated for various positions in the heating coil and the positioning coil for different coil currents to compare formulas (4) and (6).

Figure 7 shows the absorbed power in the heating coil.

As one can see, there is practically no difference in the power absorption in the center of the coil; when the sample is shifted upward or downward and out, one gets a power absorption that is up to 15% greater according to the expanded theory.

The differences are clearer in the case of the positioning coil. Figure 8 illustrates the power absorption in the quadrupole field of the positioning coil. According to the expanded theory, one finds a definitely higher power absorption than predicted by the approached theory, especially in the coil center, practically in the entire coil. When the sample is shifted out of the coil center, the relative difference becomes smaller.

There are as yet no reliable measurements of the power absorption in this coil system.

4. Discussion

4.1. Levitation Force

As one can see by looking at Figs. 5 and 6, both the approached and the expanded theory describe the levitation forces measured within the range of measuring accuracy rather very nicely; the forces were calculated somewhat too great, if anything, according to the approached theory. The deviation of the theories from the measurement values can be explained in the light of the not ideal symmetry of the really used coils and, possibly, a temperature drift of the sample that could not be quite prevented when working with the higher coil currents. The influence on electrical conductivity was not included in the calculations because this temperature change was not determined quantitatively. Estimates yielded a maximum error of about 5% in the force calculations.

4.2. Power Absorption

In Fig. 7, one can see that the two theories agree rather precisely with relation to the power absorption in the heating coil; minor deviations develop precisely in those positions where the field gradient in the heating coil becomes a maximum (Fig. 2). The absolute value of the gradient amounting to about 1 Tesla/m limits the area of validity of the approach for homogeneous magnetic fields in view of the sample radii used here and yields a power absorption that is as much as 10% too low.

In the positioning coil, on the other hand, one can find significant differences in power absorption over the entire area of the coil. The approached theory supplies obviously false values for real sample measurements particularly in the coil center where the field gradient is great, with about 1.5 Tesla/m. Looking at the entire sample, one can generally find definitely lower absorption values than one would calculate with the expanded theory because the assumption of a homogeneous magnetic field is definitely no longer met here.

5. Summary

A new, expanded theory to calculate the levitation force and the power absorption in levitation coil systems was presented. A comparison of the conventional theories and the force measurements made on the TEMPUS coil system shows that the calculation of the forces is noncritical for practical uses, so long as the samples move approximately in the coil centers, where either the magnetic field or the gradient is extensively constant in the

area of the sample. The conventional theories supply good estimates here. In calculating the power absorption, it was found that the nonhomogeneity of the magnetic fields plays a powerful role here and that the expanded theory yields a definitely more realistic estimate of the power absorption. This can be traced back to the inclusion of higher-order terms in the development of power absorption according to the sample radius and the attendant consideration of the magnetic fields that partly vary greatly over the sample.

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Design, Development of Directly Controlled Magnetic Propulsion Device for Cryogenic ARIANE5-Valve

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[Article by P. Schiebener, K. Smirra: "Design and Development of Directly Controlled Magnetic Propulsion Devices for Cryogenic Ariane5-Valves"]

[Text]

1. Overview

Short times for opening and closing, about 20 to 100 msec, cryogenic employment temperatures in the case of liquid helium or hydrogen and a small structural volume result in a requirement profile that can be met by directly-controlled solenoid propulsion devices with additional permanent magnet. The article presents the modeling of an electromagnetic circuit with permanent magnet and several utility air gaps; the solutions are presented and compared to test results on the basis of different calculation methods, the finite-element method, along with calculation of magnetic resistances in the electrical substitute circuit according to Roters (1). The mathematical layout of such a valve propulsion device—that is executed with monostable or bistable switching function—is explained and the occurring, practical problems are addressed. The available results from static and simple dynamic tests are checked for consistent information and are inserted; they can thus provide valuable supplementation for the analytical treatment of the magnetic circuit. The mathematical simulation is used also to find suitable ferromagnetic materials, that is to say, an optimum requirements profile can be drawn up for the material. The altered behavior of the magnetic circuit at low temperature can also be determined and verified because corresponding material data were determined and included in the calculation. On the basis of simulation, one can thus supply hints as to the anticipated overall behavior of the valve, these hints may serve to analyze and possibly locate low-temperature effects that occur in the integrated valve.

2. Electromagnetic Circuit with Permanent Magnet

2.1. Operating Principle

Figure 2.1.1 shows a diagram of a magnetic valve model such as it was developed in various modifications at the time for ARIANE5 uses. This is a rotationally symmetrical version of the propulsion device with redundant double coil, that is to say, the "open" and "closed" switching function is designed for an active coil only; routine operation, however, is performed with both coils activated. If the system requirements do not call for "actively redundant," then it suffices to install and use only one coil; that way one can save considerable weight.

The current part shown in the sketch with a simple seat can also be designed as a double seat or bellows version, pressure-balanced or force-controlled.

The valve is made to operate in that the permanent magnet pulls the axially movable armature down when in the closed position, thus guides the valve plunger in a force-locking manner over the interior spring and applies the corresponding seat-sealing force and seals the valve seat. To open it, the coil is activated so that the developing magnetic field inside the coil counteracts the field of the permanent magnet. If the magnetic holding force is sufficiently reduced, then the spring force of the compressed spring will prevail and the stored spring energy will lead to the acceleration of the armature until the latter has been completely pulled upward by the traction force induced by the magnetic field. Depending on the way the upper stop is made—whether with a great

or small spring tension—the valve propulsion device can perform in a monostable or bistable manner. Monostable here means that the valve again falls back into the closed position in a stable fashion after the coil activation current has been turned off; bistable here means that the assumed position is the stable terminal position, in other words, either open or closed, after the current has been turned off.

For illustration purposes, Fig. 2.1.1 also shows the ideal middle way of the magnetic flow inside the soft-magnetic materials, such as it develops on the basis of the permanent ring magnet's effect. The heavy solid line from the magnet via the armature and the armature stop ring back to the magnet is to indicate the main flow; the thin line from the main flow branching off through the armature axially upward over the upper air gap through the housing and outside downward and back to the magnet shows the very small portion that develops in the upper magnetic loop. The magnetic flow portions are exchanged, that is to say, this upper part becomes the main flow, as one can see in Fig. 2.1.2, if one looks at the open position. Figure 2.1.3 is to show the state of the magnetic flow such as one must visualize it at the start of the opening movement when one or both coils are activated in the opening direction; for the sake of clarity, only the main flows of the permanent magnet and the opposite-directed coil field are shown here. Both opposite paths can be seen along the lower contact surface between the armature and the armature stop ring, which means that the adjoining flows are weakened or compensated. Figure 2.1.4 shows the analogous situation for the open valve position at the start of the closing motion, when one works with a bistable valve version and when the valve is closed due to the effect of the current.

2.2. Magnetic Induction Sources

The design of the magnetic propulsion device presented here contains various sources of magnetic induction, depending on the operating state. In the resting state without coil activation, the permanent ring magnet supplies the two indicated magnetic circuits, that is to say, the upper and lower loops, with a stationary magnetic field. A magnetic field is generated during the phase in which the coils are activated; this magnetic field keeps growing stronger during the buildup and developmental phases and leads to counterinduction in the coil until the current flow has been stabilized. The third induction source exists when the armature moves and thus shift the portions of the magnetic flow of the permanent magnet system within the two magnetic circuits. This shift leads to a change in the flow and thus also generates an induction change.

2.2.1. Permanent Magnets

The selection of the permanent magnets is essentially determined by the marginal conditions of the valves. Employment in a wide temperature range from low temperature (20K) all the way to temperatures of about 450K in conjunction with dry long-term experiments will require permanent magnet raw materials that have thermal stability and that do not reveal any critical characteristics in the temperature range considered, such as, spin reorientation phases that can lead to temporary loss of magnetic properties. High remanence and coercive field intensities or the energy density are other important parameters in the selection of the material type in order to be able to generate sufficient magnetic holding force. Sintered magnets on a base of SECo5, such as VACOMAX170, VACOMAX200 by the Firm of Vacuumschmelze, Hanau, have proved favorable so far. (VACOMAX and VACODYM are registered trademarks of VACUUMSCHMELZE GmbH, Hanau.)

Table 2.1. Parameters of Permanent Magnet Materials

Parameter	Unit	Value VACOMAX170	Value VACOMAX200
Remanence	Tesla	0.90-1.00	0.98-1.03
Coercive field intensity	A/m	660-780	710-800
Energy density	kJ/m^3	160-195	180-210
Maximum sustained temperature	K	523	523
Curie temperature	K	993	993
Density	g/cm^3	8.3	8.4
Thermal capacity	J/kgK	370	370
Thermal expansion	$10^{-6}/K$	7	7

The company has supplied the values shown in Table 2.1 for the above-mentioned materials (2). Figure 2.2.1 shows a typical demagnetization curve B(H) and J(H) at various temperatures for VACOMAX170.

2.2.2. Coils

By applying a voltage to a cylinder coil, one can initiate the well-known effects of induction and self-induction or counterinduction in the coil; these effects can be described with the help of the following differential equation.

(2.1) Integral of E_i* ds = u_i = -dφ/dt = -d(L*i)/dt

where E_i is the electrical field intensity, s is the swept path, φ is the magnetic flow, L is the inductivity, and i is the temporally altered current.

This means that the momentary current looks like this:
(2.2) U = R*i + d(L*i)/dt = R*i + i*dL/dt + L*di/dt

Here, one must keep in mind that the inductivity L for a cylinder coil is not constant in this particular manner of use. In case of a cylindrical coil whose length l is great when compared to the dimensions of its cross section A, the magnetic resistance essentially lies inside the coil.

The following applies to the magnetic field intensity H if one neglects the magnetic resistance of the external space:

(2.3) $H = i*n/l$.

This means that the induction density B and the flow φ, per winding, turns out like this:

(2.4) $B = \mu*i*N/l$, $\varphi*A*iN/l$.

The total flow φ_g over N windings can be added up to form the following:

(2.5) $\varphi_g = N^2*\mu*A/l*i = L*i$.

Using the general relationship for the magnetic resistance:

(2.6) $Rm = l/(\mu*A)$

the inductivity L can be derived as follows:

(2.7) $L = N^2*\mu*A/l = N^2/Rm$.

Increasing through-flux or flux density inside the coil is connected with an increase in the current in terms of time; the coil is filled with the ferromagnetic armature and a movable air gap. The magnetic resistance of the arrangement grows depending on the magnitude of the applied magnetic field so that the inductivity of the circuit can be reduced. The cause of the resistance change resides in changing permeability which will be covered later.

2.3.3. Induction Change Due to Motion

Inserting a conductor in the interior of a coil induces a voltage in the coil; on the other hand, the voltage does not change when a conductor is moved axially inside a long cylindrical coil. A voltage is however induced in the coil if the flux change takes place in the interior of the coil. If one now looks at the case of the moved armature, which in a first approximation is completely inside the coil, then, as mentioned earlier, there is a change in the magnetic current distribution between the upper and lower magnet circuit. When the valve is in the closed position, the flux portion in the lower circuit prevails by far whereas it prevails in the upper one when the valve is in the open position. As a result of armature movement, for example, during opening, the main flux is increasingly shifted toward the upper circuit; this means that—even assuming a constant overall flux—the flux direction is changed in sectors of the armature which means that there is a flux change. The armature's motion speed thus also influences the flux change $d\varphi/dt$ or the induced countervoltage. Just how fast the armature moves and how it is accelerated will depend on the prevailing balance of forces which will be discussed in greater detail later (see 6).

Naturally, the above-mentioned induction sources and induction changes are mutually superposed and influence each other accordingly. The analytical treatment of the resultant effects is the subject of current and future work.

3. Forces in Magnetic Propulsion Device

The force balance is essential as far as the design and the layout of the magnetic propulsion device are concerned. It must consider all forces that occur in the course of the various operating states of the valve and the armature positions.

The great difficulty in establishing the force balance resides in recognizing the attacking forces, above all, specifying them as a function of the armature stroke. The calculation and analysis of the static force balance is a very essential step in developing the propulsion device; this step may well point up most of the problems that have to be resolved and, in the final analysis, it covers it all. In addition, it is necessary to be aware of the time-transient phenomena, even though they are difficult to determine. As examples, one might mention here only dynamic friction or the influence of the flux change on coil current development. These points must be considered in the development process by means of correspondingly large reserves.

3.1. Attacking Forces

The complex system of the magnetic propulsion device can be boiled down to a comparatively simple model, if one considers only the main forces:

-the magnetic forces induced by permanent magnet and/or coil,

-the spring forces,

-the external forces:

-hydraulic forces (flux portion) due to pressure differences,

-acceleration and vibration forces converted to static forces,

-friction and attenuation forces.

The forces listed here must be illustrated as a function of the stroke; here one must observe the distinction to the effect that there are differing stroke motions between armature and valve plunger in the propulsion system concerned; the magnet armature's stroke is greater than that of the valve plunger.

3.1.1. Magnetic Forces

The determination of the magnetic forces is one of the most difficult chapters in the force balance, not only in terms of calculation, but also in determinations by means of tests; this will be covered subsequently (see 3.3).

As mentioned earlier, the model magnet circuit of the propulsion device consists of two circuit parts that reveal one utility air gap, each, of variable length in addition to ferromagnetic material. The utility air gap turns out to be independent of the current position of the armature below and above the armature with respect to the corresponding feedback part of the magnetic force, the lower and upper armature stop. A magnetic field in an air gap between two magnetically conducting bodies leads to an attracting force between these bodies. The field can be induced by the permanent magnet or the coil or both sources are superposed. Depending on the direction of the individual fields, they strengthen or weaken the resultant magnetic field or they reverse the field direction. Then one must keep in mind that—in this design, independently of the field direction—only attracting forces are always generated, and never repelling forces; the reason for this will be discussed in greater detail later. As far as the armature is concerned, this means that the resultant magnetic force acting upon the armature is made up of two force components, both of which are pointed in opposite directions and both of which attack at the lower and upper armature end.

If induction B in the air gaps or adjoining materials is known, then the force attacking at the boundary surfaces can be calculated in analogy to the electrical field. The result here, just as it was there, is that the force attacking along the boundary surfaces is always pointed perpendicularly to the boundary surface. The traction σ_r that is aimed from a soft-magnetic material with permeability $\mu = \mu_0 * \mu_r$ at the air amounts to the following:

(3.1) $\sigma_r = (\mu_r - 1)/(2*\mu_r*\mu_0)*(B_n^2 + \mu_r*B_t^2)$,

when B_n and B_t refer to the normal and tangential components of the flux density in the air space. For small air gaps and perpendicular induction flux through the pole surfaces with cross section A—such as they are encountered in this case—one can use the following simplified formula for $\mu_r >> 1$:

(3.2) $F = \sigma_r*A = 1/2*B^2*A/\mu_r$,

where B is the induction in the air gap.

The way leading to the calculation of the applied flux density B will be discussed in greater detail in Point 4.

3.1.2. Spring Forces

Cylindrical helical springs arranged inside the armature for reasons of space support the opening and closing activities of the valve and partly store the armature's kinetic and magnetic energy. The spring rates are determined very carefully because, in the force balance, they must harmonize mostly with the (electro)magnetic forces. For this purpose, the number of windings and the terminal positions of the springs are optimized to supply maximum force at minimum spring volume. The spring sizes are calculated for cylindrical helical springs according to DIN 2089; the springs are measured carefully prior to integration to check on accuracy. If an operating point of the valve is to be expected at higher temperatures, for example, $T > 330K$, then one must provide for and carry out thermal aging or exposure to load.

3.1.3. External Forces

The point entitled "External Forces" subsumes the forces that attack the magnetic propulsion device from the outside, that is to say, the hydraulic forces that result from the flow portion of the valve, more specifically, on the valve plunger, and the acceleration forces that appear during the starting phase, phase separation, etc. Besides, the closing force on the seat is absorbed as a reaction force because the latter determines the degree of tightness. The sector of permissible leakage extends from 10 scc/s to the lower extreme value of 10^{-8} scc/s, depending on the specification related to the gaseous helium flow, such as, for example, in the case of the ISO satellite (Infrared Space Observatory).

3.1.3.1. Hydraulic Forces

The hydraulic forces are generated by pressure differences that act on various surfaces. This force varies depending on the operating state; the essential parameters are the input pressure, the mass flow, and the reverse or output pressure. The calculation must be performed in such a way that the maximum forces will be considered, that is to say, one must form the sum of the following products:

(3.3) $F_{hydr} = \Sigma_i(F_{max})_i = \Sigma_i(A_{max})_i*P_i$.

As for the individual maximum surfaces (A_{max}), for example, the relatively soft, deformable valve seat surfaces, one must accordingly also consider elastic deformations that are determined either by calculation or by experiment. This can be done comparatively simply, at least during the stable terminal positions, that is, open and closed. The pressure loss or the pressure difference in the open valve position as a rule is a part of the component specification and must therefore be evidenced mathematically or through testing so that this value is to be assumed to be known.

Both the calculation effort and the test effort are very great for the intermediate stroke positions because the movements take place very rapidly and because one must consider the nonstationary pressure development over the valve. Because the pressure development naturally depends on the medium, the pressure, and the temperature, one must set either original conditions or carefully selected reference conditions. When one uses hydrogen or oxygen, the safety requirements are to be made so stiff that, in practice, one can fall back as much as possible to the reference experiments with nonhazardous fluids, nitrogen, or water. The hydraulic force will be taken to be constant with the maximum occurring force and the reduction via the stroke will be neglected during the developmental phase on account of the effort to be made, assuming this is justifiable on the side of safety.

3.1.3.2. Acceleration and Vibration Forces

The acceleration forces that act on the valve and the valve drive as a rule are given in the specification of components. That includes the essential operating states or maximum values, such as they appear at the start, during phase separation or control maneuvers. The superelevations on account of resonance effects which must be considered here and that relate to the entire environmental structure and that are also set from there are, as a rule, determined mathematically and minimized if possible and are evidenced in vibration tests on a shaker. Conversion to a maximum acceleration a then yields the acceleration force F_a:

(3.4) $F_a = \Sigma_i(m^*a)_i$.

These forces must mostly be shielded against the propulsion device for open or closed valve positions; but switching during these phases may also be specified so that these forces also are at work during the transient phase.

3.1.3.3. Seat Closing and Sealing Force

The seat sealing force, which is necessary so that the specified leakage will not be exceeded, must be determined experimentally with the corresponding seat configuration. The connection between the seat sealing force and leakage is heavily nonlinear because the leakage flux volume depends on the flux mechanisms and flux shapes, such as they develop for these conditions. This is why one must consider the seat sealing force as an external, predetermined force that the propulsion unit must provide and that it transfers to the valve plunger via spring action. The sealing forces of the various seats made are between about 100 N and 200 N; in addition to the leakage, it is naturally also the dependence of the valve seat size that is decisive.

3.1.4. Friction and Attenuation Forces

The calculation of the friction forces as a rule can only be a rough estimate because there are too many uncertain factors and imponderables.

The friction to be considered here occurs above all between armature and housing, in the passageways of the entire valve plunger, as well as between the sealing seat. By way of example, one might mention the problem complex occurring in connection with the determination of the friction that applies analogously to other points of contact and motion as pointed up by the pairing of armature and housing.

The friction coefficient between the surfaces of the armature and the housing can be assumed to be in the order of magnitude of μ = 0.1-0.2. The magnetic force that acts radially in the ring gap around the armature, however, is unknown because the armature does not run concentrically with respect to the housing but rather rests unilaterally against the housing with line or surface contact. The size of the radial gap on the non-adjoining side differs due to manufacturing tolerances. The armature's resultant radial force F_{radial}—on an order of magnitude of up to 80 Newton—when multiplied with the friction value μ leads to the mathematical friction force $F_{fric,i}$; the sum of all developing individual frictions yields the total friction force F_{fric}:

(3.5) $F_{fric} = \Sigma_i(F_{fric})_i = \Sigma_j(F_{fric})_j + (F_{radial})^*\mu)$.

Because the friction coefficient μ when used at low temperature appears as a function of the temperature, surface configuration, and other influencing magnitudes that can be determined only in a very uncertain fashion, one can make a sure statement about the magnitude of the friction force only by means of a test evaluation using the original part.

Regarding the attenuation forces, one must in particular observe the gas compression in the interior propulsion unit parts. The displacement of the gas volume above and below the moving armature takes place during every switching cycle via the outer armature ring gap or corresponding relief boreholes in the armature. On account of the rapid process, one can determine isentropic, adiabatic state changes and the influence on the armature's movement. The dynamic effect of this gas spring is small because the enclosed gas volumes are very small.

3.2. Measuring the Forces During the Test

When one uses ferromagnetic material in the magnetic circuit, the magnitude of the developing force depends very much on the material's magnetic antecedents, that is to say, the size and direction of the last-adjoining field. This is why the sequence according to which the magnetic forces are measured is important; it must be equal to the sequence involved under operational conditions. Looking, for instance, at the determination of the holding force in the bistable, open terminal position, this means that a current pulse must be given in the opening direction before one measures the force required to move the armature in the closing direction. These rather laborious appearing procedures are necessary to simulate realistic conditions as regards magnetic hysteresis and friction.

3.2.1. Magnetic Forces

The magnetic forces are measured as a rule with original parts, but without springs, in special, traction-pressure-resistant force measurement testing arrangements with path resolution in the μ range, observing the required switching sequence. Measurements with coil activation here represent the maximum attainable force curve because the current in the coil is fully developed by virtue of static measurement, whereas in the real switching process, the current still develops in an ascending fashion so that the maximum force has not yet been attained corresponding.

Figure 3.1 shows examples of measurements of force vs. stroke for monostable or bistable switching procedures.

The difference in the force of the currentless curves can be traced back to friction and magnetic hysteresis. One could reduce the magnetic hysteresis to a minimum by means of demagnetization, but one would then no longer speak of real switching behavior.

3.2.2. Pull-In Current

The measurement of the so-called pull-in current yields the minimal current intensity necessary in order to open or close the valve completely. The recording and analysis of the current curves will supply valuable references as to the valve's switching performance. Among other things, one can determine the valve's switching time very accurately. As indicated earlier in the point entitled "Induction Sources," the coil current is subjected to the influence of the induced voltages. The temperature is a main influencing parameter; it influences:

-the speed of armature movement due to altered friction behavior and altered spring properties,

-the magnetic properties of the permanent magnet,

-the magnetic properties of the ferromagnetic materials,

-the coil's ohmic resistance.

The coil's ohmic resistance drops quite considerably if one works at cryogenic temperatures; this leads to a steeper current rise in the coil, see equation (2.2).

Figure 3.2. shows the current-time measurement recording of an opening procedure at room temperature; Fig. 3.3 shows the analogous experiment at low temperature.

The difference between the maximum attainable current on the basis of voltage supply or current limitation and the current actually needed for switching is a measure of the current reserve, equivalent to force reserve, which is still available.

The time difference between the extreme current values in the first approximation is the armature movement time during which counterinduction is at work; that way, one can easily determine the valve's switching time. If the curve is resolved with sufficient accuracy, one could also calculate the armature's acceleration and speed from the gradient of the descending current curve, as well as the currently prevailing force that acts on the armature.

4. Calculation of Magnetic Forces

In practice, the calculation of the magnetic force can basically be broken down into two different methods:

-method of calculating magnetic resistances in the electrical substitute circuit diagram, assuming that one already has a good knowledge of the magnetic flow's path;

-accurate calculation with field-theory setups:

-magnetic potential to scale,

-vector potential.

These two setups are treated with small-structure models, such as finite-element methods, finite-difference methods, and can be put into and calculated in corresponding programs. So far, model calculations have been performed with the program systems ANSYS (3), PROFI (4), and FEMAG (5). Subsequent statements and comparisons relate exclusively to FEMAG.

4.1. Method of Calculating Magnetic Resistances in Substitute Circuit Diagram

This method is based on the analogy of the electrical and magnetic circuit, so that one can apply Kirchhoff's laws with the junction and mesh rule and so that one can define voltages, voltage sources, current density, and resistances. Table 4.1 shows a list of analogous magnitudes in the electrical and magnetic fields.

Let us assume that we have the following:

- homogeneous flux distribution in conductor material,

- constant cross section along path,

- constant substance property μ within a conductor element.

One can then determine the magnetic resistance, for instance, of a cylinder with length l and cross section surface A through which current flows axially, as follows:

(4.1) $Rm_{axial} = l/(\mu^*A)$.

One gets the following for a cylinder with height z and radii R_a and R_i through which current flows radially:

(4.2) $Rm_{radial} = \ln (R_a/R_i)/2(^*\pi^*\mu^*z)$.

The following product must be inserted for the permeability μ:

Table 4.1. Analogous Magnitudes in Electrical and Magnetic Fields

Electrical field magnitude	Unit	Magnetic field magnitude	Unit
Voltage	V	Voltage, through-flux	A
U, Field intensity, E	V/m	θ, Field intensity, H	A/m
Current density	A/m^2	Induction, flux density	Vs/m^2
J, Current intensity, I	A	B, Magnetic flux	Vs
Electrical field constant	As/Vm	φ, Magnetic field constant	Vs/Am
ε0, Dielectric constant	-	μ0, Relative permeability	-
e, Resistance, R	Ω	μ_r, Resistance, Rm	1 Henry

(4.3) $\mu = \mu_0^*\mu_r$.

The value for μ can be taken as differential permeability directly from the B-H material diagram because the

permeability is defined as proportionality factor in the relationship between field intensity and flow density:

(4.4) $B = \mu * H$

From this, one can then derive that the equations for the resistance depend implicitly on Induction B

(4.1b) $Rm_{axial}(B) = 1/\mu(B)*A)$

(4.2b) $Rm_{radial}(B) = \ln (R_a/R_i)/(2*\pi*\mu(B)*z)$.

These considerations also apply to the permanent magnet whose values can be taken from the characteristic lines. In the case of soft-magnetic materials, the difficulty only consists in the fact that the characters decline, such as it is usually known—see Fig. 4.1—for the material 1.4006 at room temperature, presupposes a field intensity curve of the hysteresis that changes from very high positive values to very big negative ones and back to high positive ones. The field intensity's change inside the propulsion device, however, moves only within a small segment in so-called partial hysteresis loops whose curve ascent can deviate considerably from the known material curve. The error remains within limits because the hysteresis loop is most very narrow, related to the field intensity H, in the case of soft-magnetic materials; otherwise, the curve of the partial hysteresis loops must be inserted; Jiles, for example, offered calculation proposals for this (6).

The valve magnet drive can be assembled as a parallel and series circuit of resistances and voltage sources; related work was done and improved in the context of studies and dissertations (7). The individual geometry elements that have current flowing through them are calculated as resistances. The substitute circuit diagram of a propulsion device is shown in Fig. 4.2; the area surrounding the permanent magnet is shown in detail and enlarged in Fig. 4.3. The more refined the distribution of the individual resistances, the better will the calculated results turn out. The iterative calculation of the current density and flow density distribution in the final analysis leads to the determination of induction in the two air gaps below and above the armature so that the resultant armature force can be calculated as a difference between the two individual forces. The calculation accuracy that can be attained in this way can be estimated on an order of magnitude of about 10%; mathematically and experimentally, that can be considered to be very good when it comes to magnetic force determination.

4.2. Calculation Using FEMAG Finite-Elements Program

The FEMAG finite-elements program (5) solves the system equations of the initially unknown vector potential and makes it possible to calculate the force alternatively via the calculation method of Maxwell's stress tensor or via the method of virtual works. The characteristic magnetization lines of the various materials are inserted here and an independently performed grid refinement routine takes care of optimum lattice grid distribution related to the problem as such, for example, force calculation. Figure 4.4 compares the forces calculated according to 4.1 and 4.2 to the measured values.

4.3. Analysis of Magnetic Circuit Calculation

The analysis of the magnet circuit calculation is not confined only to the determination of the occurring and available forces; instead, it also supplies an idea as to the distribution of induction. In this way, one can locate magnetic "bottlenecks" that reveal strong resistance which either results from geometric design reasons without wishing it so, or that is intended so as to achieve a well-defined induction or force curve. A sensitivity analysis about magnetically critical places can thus yield an accurate material requirements profile that will help determine the selection. Mathematical simulation is better suited for this than expensive test series. Often, rougher mathematics models suffice to be able to make on-target trend statements. Considering the material data for low temperature, one can also better interpret the refrigeration experiments because one can calculate the forces and one can assume them to be known. Any appearing low-temperature effects can then be analyzed better with the help of this information.

5. Magnetic Material Parameters

The magnetic material properties depend on a series of parameters that are technically relevant, especially when low temperatures are used. Mechanical stress states, for example, influence the permeability in such a way that traction stresses cause the relative differential initial permeability to rise, whereas pressure stresses lead to a decline. This effect can become noticeable because, during cooling, thermal stresses develop between different materials that have been welded together.

The magnetic material parameters also change due to the influence of temperature. Here, the sensitivity toward increased temperatures is greater than toward low temperatures. With some exceptions, as mentioned earlier in 2.2.1 in relation to permanent magnet materials, the ferromagnetic materials behave in keeping with the tendency they reveal in response to ambient temperature. Figure 5.1 shows how a soft-magnetic material is qualitatively a function of the saturation polarization J:

(5.1) $J = B = \mu_0 * H$

from the temperature up to the vicinity of the absolute zero point. Corresponding measurements must be performed because these values are usually not available. That happens, for example, in case of a squid magnetometer in which spherical or cylindrical samples of the material to be investigated are measured magnetically at various temperatures. Figure 5.2 shows the processed values deriving from a hysteresis measurement at temperatures of 10 K and 300 K. The values illustrated in terms of emu units (electromagnetic units) are to be converted via the corresponding geometry-dependence demagnetization factors into polarization or induction

values; see Fig. 5.3, J-H diagram for material 1.4006 at room temperature and low temperature.

6. Balancing the Forces

Once the essential influencing magnitudes and forces are known at last, one can determine the spring forces that are to be adjusted from the balancing results. Here one must observe or distinguish the corresponding operational conditions:

monostable switching performance:

- opening and holding in open position with coil activation,

- closing and holding in closed position without activated coil(s);

bistable switching performance:

- opening and closing with coil activation,

- holding in open and closed position without activated coil(s).

Figure 6.1 shows an example of a graphic force balance for a monostable propulsion unit. For the sake of greater clarity, the hydraulic force already includes seat friction or the curves of the magnetic forces also contain the friction forces of the armature, etc., because these are forces that are determined in the course of experiments with original parts. Besides, acceleration forces on the order of 30 times terrestrial acceleration are included in the calculation.

7. Summary

The design and layout of an electromagnetic propulsion unit for cryogenic valves to be used in space flight must include consideration of a series of marginal conditions that require great circumspection and that partly extend all the way into technical virgin territory. The availability of material data for cryogenic temperatures is limited and must frequently be supplemented with measurements that establish and necessitate stiff technical requirements. The calculation of the magnet circuit can yield carefully evaluated test results up to about 5-10% with respect to the forces. The method according to Roters supplies results that are just about as good as complex finite-element calculations—assuming that the most probable path of magnet flow is known. This statement applies as long as one can rule out strong material saturation phenomena. The quality of the mathematical calculation results as regards comparability with test results will generally depend very much on the employed magnetic material parameters that are definitely scattered in practice.

8. List of Frequently Used Formula Symbols

A—Cross section surface, attack surface B—Magnetic flow density E—Electrical field intensity F—Force I, i—Current, alterable in terms of time H—Magnetic field intensity l—length L—Inductivity N—Number of windings R—Electrical resistance Rm—Magnetic resistance t—Time U, u—Electrical voltage, alterable in terms of time φ—Magnetic flow σ_z—Voltage in z-direction μ—Permeability, friction coefficient μ_r—Relative permeability μ_0—Vacuum's permeability θ—Flow-through

Indices

i—Counting index mag—Magnetic n—Normal r—Relative t—Tangential.

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Germany: Technology Development During Manned Space Flight

EUROKOSMOS

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[Article by Guenter Schmitt, Manfred Krischke, Kayser-Threde, GmbH, Munich: "EUROKOSMOS"]

[Text]

1. OVERVIEW

Kayser-Threde has been working on cooperative projects with organizations in the CIS since 1984 and carried these projects out with support from DARA and ESA.

EUROKOSMOS is a joint project of Kayser-Threde and CSKB calling for a complete capsule mission annually starting in 1994. Kayser-Threde booked five CSKB missions on the basis of good experiences with past projects.

EUROKOSMOS will used a modified space vehicle from the FOTON family with special technical properties deriving from FOTON, BION and RESURS. This makes for a huge battery capacity, vacuum connection, pressure-tight capsule, "late access" access and position regulation capacities (Earth alignment). EUROKOSMOS will be placed in a near-Earth orbit with the help of a SOYUZ rocket.

EUROKOSMOS will employ the spacecraft's own TM/TC systems for flight monitoring from Moscow, while an infrastructure developed and built by Kayser-Threde will facilitate monitoring and performance of experiments on-board from Western Europe.

The infrastructure for EUROKOSMOS experiments consists of a "data handling system" on a transputer base, TM/TC/TV systems and universal assembly frame with defined cooling possibilities. The infrastructure thus meets the requirements of "European" experiments and facilitates simple adaptation of existing experimental instruments on the basis of their flexibility.

Potential customers will come from the following fields:

- low-gravity research,

- re-entry technology,

- small satellites,

- technological experiments.

The possibility of monitoring and, perhaps, taking corrective action regarding on-board instruments and experiments from any ground stations in Western Europe via Telescience in EUROKOSMOS will facilitate not only the accomplishment of the scientific mission but will also create ideal testing conditions for future Columbus applications.

A EUROKOSMOS flight will be carried out within a time span of 14-16 days.

2. INTRODUCTION

There are increasing efforts on the part of international sources to carry out joint projects in view of the tremendous space flight know-how available in the CIS countries, as well as in the light of the economic situation and the attendant available capacities in the CIS space flight industry.

Kayser-Threde has been working intensively on projects with organizations in the CIS since 1984. During that time, numerous joint undertakings and joint flights were carried out on Russian vehicles with support from DARA and ESA.

EUROKOSMOS is a joint project—initiated by Kayser-Threde—with CSKB, the Central Specialized Design Bureau in Samara, Russia, in connection with which one complete capsule mission is to be flown annually starting in 1994. In the light of good past experience, Kayser-Threde has scheduled five CSKB missions. The basic idea behind EUROKOSMOS is to provide Russian systems with Western data processing and telecommunications systems to meet the demands of Western users offering advantages, such as extreme reliability, short preparation times, and reasonable prices.

3. CONCEPT

The Foton spacecraft family of the CSKB is the basis of the EUROKOSMOS craft. Many hundreds of military and civilian missions have been accomplished with this family since the sixties.

The Russian capsule missions are usually flown depending on payload with the following spacecraft types:

- FOTON for material sciences,

- BION for "life science,"

- RESURS for Earth observation.

EUROKOSMOS combines technical properties of the three spacecraft types: from FOTON, it gets the big battery capacity and the vacuum distribution system; from BION it draws the pressure-tight capsule with the "late access" possibility; and from RESURS, finally, comes the expanded position regulation capacity for Earth alignment.

The general technical conditions of the Russian vehicle can be gleaned from the following table:

- Payload weight	1,620 kg
Experiments	420 kg
Batteries (6,000 ampere-hours)	1,200 kg
- Payload volume in space inside capsule	1.5 m^3
- Payload capacity on spacecraft outside	see Chapter 6.2
- Thermal monitoring, average inside temperature of capsule	15°C-25°C
- Interior capsule atmosphere	1 bar air
- Vacuum distribution	10^{-3}-10^{-4}mm Hg
- "Late access" up to	-2 hrs prior to launch
- Position adjustment	

4. INFRASTRUCTURE

The spacecraft will be operated via Russian systems from Moscow; for operation and monitoring of experiments, EUROKOSMOS has its own data handling and control system as well as a modern telecommunications system that is operated from Western stations.

The data handling system is built up in a modular fashion on the basis of T425 transputers made by Inmos. It consists of diverse DHS base modules, the memory modules, and periphery interfaces.

The base modules process the data from 16 analog and 32 digital channels that can be configured byte-wise as input or output channels.

All modules are interconnected via transputer links. Communication between the individual models takes place via these links.

This structure facilitates:

- parallel data processing,

- redundant build-up because all base modules can access the memory module independently of each other.

The analog channels are scanned by base modules with the same frequencies; the scanning frequencies are not synchronized.

On the base modules, there is a real-time-clock subassembly with calendar function that is buffered by an external battery, just as the SRAMs of the working memory.

The system can be expanded in almost any desired fashion. Subsystems can be connected either directly via transputer links or via RS422 serial interfaces.

The storage capacity of fixed-value memories is graduated from 16 Mbytes all the way to 128 Mbytes, whereas more than 1 Gbyte can be stored per DAT recorder used.

The EGSE is connected via a transputer link. Four separate signal lines ensure effective debugging of the implanted software for first-time tasks.

Experiments are supplied with electrical energy either via the batteries supplied from the spacecraft or via their own batteries. With a voltage of +27 +4/-5 VDC, the spacecraft itself supplies a battery capacity of 6,000 ampere-hours. The possible average electrical output is 400 W, the peak output is about 700 W for 1.5 hr per day.

5. TELECOMMUNICATIONS

Communication with the experiments during mission operation will be handled via Western stations.

Kiruna/Sweden, Fucino/Italy, and Oberpfaffenhofen/Germany are earmarked as ground stations.

This results in the following ground contact times with an orbit inclination of 62.8°:

-Kiruna with an elevation of > 5°: 4 contacts per day with about 8 min, each time;

-Fucino with an elevation of > 5°: 3 contacts per day with about 7.5 min, each time;

-Kiruna and Fucino with an elevation of 0°: 3 contacts per day with 15 min, each time;

-Kiruna, Fucino, and Oberpfaffenhofen with an elevation of > 5°: 3 contacts per day with about 15 min, each time.

The transmission times can be made considerably longer if a relay satellite is used later.

The communications system employed here corresponds to the flight-tested MAXUS system. It is equipped with the following:

-up to 8 TV plugs, PAL, CCIR 405/625 lines, whose intermediate storage is accomplished on individual on-board recorders with up to 4 hrs of continual recording capacity;

-2 telemetry segments, 128 kbit/sec for the dump of selected data;

-449.95 MHz remote control segment with 3 x 1 TC channels, with 160 updates/sec and 7 x 8 TC channels, with 20 updates/sec, or 5 x 8 TC channels with 20 updates/sec 2 x 1 RS422.

Instead of an alignment of the spacecraft or the on-board antennas, transmission takes place via an antenna system with switchover to the antenna that may be most effective with respect to the ground reception station at any particular time.

6. USERS

The EUROKOSMOS concept offers flexible joint-flight opportunities for a broad range of experiments from microgravitation research and technology testing.

6.1. Interior Capsule Space

Plans call for experiments and instruments:

-that come from the TEXUS/MAXUS, EURECA/GAS areas as well as SPACELAB/COLUMBUS;

-that were developed for use in Russian capsules;

-that are of Russian origin;

-that serve to test satellite communication, telescience, and expert systems, robotics and automation.

In the field of robotics, EUROKOSMOS opens up possibilities for moderately-priced in-orbit testing of components or systems in both automatic and remote-controlled modes.

The joint flight of the ROTEX telerobotics experiment would be an example of such a mission.

6.2. External Payloads

EUROKOSMOS offers a possibility of carrying payloads outside the capsule; the accessory battery container can also be replaced by a payload.

The payloads can be operated both autonomously and they can get energy and control signals also from EUROKOSMOS.

6.2.1. Mirka/Rapunzel [Little World/Lamb's Lettuce]

The first EUROKOSMOS mission will include the Mirka capsule that was jointly developed by Jena Optronik and Kayser-Threde.

This is a small, autonomous re-entry capsule that sits "piggyback" on the EUROKOSMOS capsule; it is supplied with thermal energy from EUROKOSMOS during the orbital phase; it is braked together with the big capsule; finally, it re-enters autonomously. The capsule is used, on the one hand, for a series of re-entry experiments; on the other hand, it means that Germany has now gotten into the business of capsule technology and it represents the development of an efficient system for future uses.

The plans for a second mission call for the Mirka capsule to carry out a first German tether mission called Rapunzel.

Mirka is to be pushed off EUROKOSMOS, but it will remain connected to it by a thin cable. Because both mother-satellite and daughter-satellite move along differing orbits, they travel apart from each other, while the cable is being paid out. Starting as of a certain cable length, the pay-out procedure mostly takes place between mother-satellite and daughter-satellite on account of the gravitation gradient. After the cable has reached its maximum length of about 50 km, it is capped and the Mirka capsule moves to a re-entry orbit on account of the special orbit mechanics or the exchange of moments with the big capsule.

6.2.2. Re-entry Experiments

The EUROKOSMOS re-entry capsule offers the possibility of performing experiments on the stagnation-point side during re-entry into the Earth's atmosphere. The spectrum extends from passive material samples, such as they were flown on Foton already this year, all the way to active, instrument-backed experiments.

6.2.3. Biopan

Biopan is an ESA unit for life-science experiments that was developed by Kayser-Threde for Foton. It is attached on the capsule's outside. It makes it possible to expose biological samples in a temperature-regulated fashion to the spacecraft's environment. The instrument has a heat shield and goes through the re-entry on the capsule.

6.2.4. Rendezvous and Docking

The performance of rendezvous and docking maneuvers or experiments constitutes yet another way to make use of the outside payload possibilities offered by EUROKOSMOS. Here, it might be conceivable, for example, to combine EUROKOSMOS and Mirka for an in-orbit testing of the rendezvous and docking sensors and to employ the necessary adjusting algorithms or to perform a complete coupling maneuver.

7. EUROKOSMOS-1

At this point in time, one can detect the following payload configuration for EUROKOSMOS-1:

-The Biobox and another ESA experiment, as well as IBIS from CNES [National Center for Space Studies] are earmarked for use in the capsule's interior space. DARA participates in the mission to the extent of 30% but has not yet specifically indicated the experiments.

-MIRKA and BIOPAN are planned as external payloads.

Some of the experiments require "late access" prior to launch and "early retrieval" after recovery.

The mission is scheduled for the first half of 1994!

8.SUMMARY

EUROKOSMOS is a German-Russian cooperation project under the management of Kayser-Threde. The combination of a Russian space vehicle (Foton) with Western electronics offers manifold possibilities for integrating and carrying out experiments. The main advantages consist of the reasonable costs, short preparation times, great flexibility, reliability, and small documentation effort.

Kayser-Threde has booked five missions; the first one is scheduled for 1994.

The launch will be made with a SOYUZ rocket in Plesetsk; capsule landing and recovery will occur in Kazakhstan.

Germany: Technology Development During Manned Space Flight

Development of Cryogenic Infrared Fabry Perot Spectrometer for ESA IR Space Observatory

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[Article by J. E. Stocker, Max Planck Institute for Extraterrestrial Physics: "Development of a Cryogenic

Infrared Fabry-Perot Spectrometer for the Infrared-Space Observatory of ESA"]

[Text]

1. INTRODUCTION

The Infrared Space Observatory (ISO) that is to be launched by ESA, the European Space Agency, in May 1994 consists of an optical telescope in a cryostat with four scientific instruments in the focal plane which, together, facilitate imaging, photometric, spectroscopic, and polarimetric observations in the wavelength range from 2.5 to 200 μm (see Fig. 1).

The scientific instruments are on the rear of the supporting structure for the 60-cm reflector of the Richey-Cretien telescope.

The 20-arc-minute unvignetted vision field of the telescope is distributed radially over the four instruments in the focal plane via a pyramidal reflector (1).

One of the four instruments is a short-wave grating spectrometer (short-wavelength spectrometer, SWS) that covers the wavelength range from 2.5 to 45 μm with a spectral resolution of 1,000.

A scanning Fabry-Perot interferometer is connected behind the spectrometer in order to investigate the range from 15 to 25 μm with a spectral resolution of $2x10^4$. The latter was developed by the Max Planck Institute for Extraterrestrial Physics in Garching near Munich (2).

2. DESIGN CRITERIA

-Minimizing current consumption and thus heat output to extend the operational service life of the cryostat in orbit which should be at least 18 months for ISO.

-Weight restriction. ESA was able to allocate only 7.5 kg for the entire SWS short-wave spectrometer; only 500 g are left for the Fabry-Perot interferometer.

-Extreme shape stability. The instrument is to be lastingly deformed by no more than just a few 1/1,000 degree due to thermal stresses, such as cold cycles with a space temperature of 4 K, or mechanical stresses, such as the extremely high vibration accelerations during rocket launch.

3. PROBLEM SOLUTIONS

The entire wavelength range is covered by two individual Fabry-Perot interferometers (FP's); one extends from 15 to 25 μm and the other one from 25 to 35 μm. It was decided to provide only one common drive mechanism, because only one of the two FP's is in operation at any one time.

Figure 2 shows a diagram of the FP system. One reflector, each, of the two interferometers is on a common base plate. The drive mechanism for adjusting the reflector interval consists of three activators, each of which works against an associated spring. Activators and springs have common action axles so that no bending moments of any kind will be injected into the system.

The reflectors consists of a mesh grill of 5 μm thick, gold-coated nickel mesh with grid constants of 10 μm and 6.6 μm. To scan the entire wavelength range, the reflectors must be moved over a total stroke of 22.5 μm in 40-nm steps, if one assumes a finesse of 50 for each of the FP's and a stroke resolution that is at least three times greater than the optical resolution.

Basically, the FP system is to be as simple and rigid as possible. Any kind of adjusting screws or similar devices should be avoided.

Instead of regulating the interval and the parallelism of the reflectors by separate devices, both tasks are accomplished by only one set of three identical actuators.

One can attain either a procedure or a parallel-setting by impacting these actuators with identical or slightly different currents.

The latter makes it possible to correct maladjustments that originated from processing and assembly or due to shape changes after some cooling cycles.

It is assumed—and all tests confirmed this—that the actuator current that regulates the interval of the reflectors does not change with the passage of time and the temperature.

This is why this current is used as the only position indicator for the reflectors and no additional position indication sensors were built in to keep the system as simple as possible. But parallelism and position sensitivity should occasionally be checked in orbit with the help of the spectral lines of a built-in calibration source.

3.1. Actuators

Different types of actuators were investigated. Piezoelectric systems were ruled out on account of their great hysteresis and their high voltages; and, using electromagnetic plunger coils, one can hardly make the necessary short motion steps for a relatively rigid mechanical system.

Actuators of the type of lifting magnet with a small air gap appeared to be best suited for this use. One can easily generate forces amounting to several Newtons with very little output for a stroke of 20 μm.

The stroke of such an actuator is proportional to the supplied current as a nonlinear function. Only the coercive force of the soft-magnetic material brings about a certain hysteresis and must therefore be sufficiently small.

The coercive force from standard soft-magnetic material rises by a factor of up to 10, if it is cooled down to 4 K; this is why it was necessary to find a material with little temperature dependence.

In the end, CRYOPERM 10 made by Vakuumschmelze Hanau was adopted; at 4 K, it has a coercive force of 6 mA/cm; that is sufficiently small (3).

Figure 3 shows a complete actuator with spring system. A spring system consists of two pairs of leaf springs whose resultant active force vector coincides with the actuator's force vector. One pair is connected with the system's mobile base plate and thus with the lifting magnet lid; the other one is connected with the fixed base plate via the lifting magnet pot. The air gap is set via an adjusting ring whose height can be coordinated.

Each individual component of the assembled system must be lapped in terms of parallelism and flatness for ≤ 0.002 degree to attain an initial parallelism of ≤ 0.7 µm degree in the FP units.

3.2. Base Plates

The system's simple structure and the high requirements for accuracy demand materials with extremely good shape stability over a wide temperature range, especially as regard the base plates.

Only aluminum could be considered here on account of weight reasons. But most aluminum alloys that were tested revealed permanent deformations that were far above the permissible measure after several temperature cycles. Only one material proved to be suitable, and it is relatively new on the market. This material is Dispal 2 by Krebsoege, a sinter aluminum with a noncrystalline structure but with high tension resistance amounting to 370 N/mm^2.

Figure 4 shows interferograms of one of the two FP's before and after cooling to 6 K. After cooling, one can see one additional stripe. This means that the angle between the two FP reflectors changed only by 0.0005 degree due to the temperature change; that is permissible.

Another quality requirement for the base plate material has to do with internal attenuation and its temperature dependence. Because the interval of the reflectors is changed via individual steps, the system begins to oscillate at every step and one cannot start the measurement until these oscillations have faded. This is why we investigate the temperature dependence of the Q quality factor for three aluminum materials; Q here is proportional to the internal attenuation. A low-quality factor implies a high internal attenuation.

Figure 5 shows the result. Here again, Dispal 2 proved to be the definitely better material (4).

3.3. Mesh Holder

The system is operated at room temperature and at 4 K; this is why the mesh grills of the reflectors must reveal almost flatness over the entire temperature range.

This requirement and the fact that the mesh consists of nickel, whereas the base plate material consists of aluminum, calls for some effort.

Figure 6 shows how this problem was solved. The actual mesh holder is a tension ring on which the meshes are glued. GE 7031 was used as adhesive; it is qualified for temperatures of up to 3 K.

Prior to gluing, the meshes were so prestressed with a special tool that the tension would be uniformly distributed over the mesh.

To maintain this prestressing during cooling, the heat expansion coefficients of the materials used for the tension ring and the mesh must be so coordinated that the meshes will remain prestressed but will not be plastically deformed. 9S20 K, a carbon-poor steel, is suitable as tension ring material for nickel meshes.

The actual reference surface for the reflectors consists of ring-shaped bulges on the base plates that were lapped upon the required planeness and that were stretched over the meshes like a tympanum. For this purpose, the tension rings—that do not have any direct contact with the base plates—are pulled in the direction toward the base plate by means of three clamps each.

As a result, the nickel mesh can move with respect to the aluminum base plate during cooling without any change in the mesh tension and the planeness of the reflectors remains preserved.

With the help of this arrangement, one can simultaneously solve another problem, that is to say, the long after-oscillation of the nickel meshes at 4 K, when the latter are excited into oscillation during the step-by-step setting of the reflector interval. The small relative motion along the grill support generates friction that reduces the after-oscillation to about 2 sec, as against 5 min in another arrangement.

4. PERFORMANCE

Figure 7 shows two section views of the Fabry-Perot interferometer. Here, one must note that wherever differing materials interface, the coupling is made only via one single point, mostly the center of the component, in order not to initiate any warping and, thus also, distortions during cooling. That is something one can see particularly when looking at the section through an actuator-spring package.

But the entire system is hitched to the SWS only in the center by means of two thermal length-compensated screws that are close together. It took two screws to secure the FP against being twisted.

Figure 8 shows the integrated instrument and the essential individual components.

5. TESTS

A φ 100-mm CO_2 laser beam with beam divider plus either a camera or a photodetector for registration were used to measure the planeness and parallelism of the reflectors.

To prevent tensions generated by this double screwing arrangement from causing deformations of the base plate, the initial screw-in area was disconnected from the remaining base plate by a ring-shaped groove.

The temperature of the instruments is measured by means of a semiconductor temperature sensor that is integrated into the mobile base plate. The electrical connections are made via circuit boards with soldering terminals.

The FP was cooled to 4 K with a helium Dewar. It took a special helium Dewar to perform vibration tests at 4 K. It had to be vibration-proof itself and was not to have any inherent resonances in the excitation range. The Fabry-Perot interferometer passed all qualification tests successfully.

6. SUMMARY

It was possible to develop a Fabry-Perot interferometer that corresponds to the objectives in all details. A total weight of 450 g and a maximum current consumption of 2 MW was achieved by special design solutions and with the use of unconventional materials. The reflector non-parallelism due to thermal deformation and maladjustment due to vibration stress amounts to 0.003 degree and can be corrected easily by means of the actuators.

Figure 9 shows a complete scan of 500 individual steps over two orders of emission lines of a calibration source built into the SWS at 24 μm.

7. ACKNOWLEDGMENT

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